the Cosmology of now & then through first light

Dick Bond Canadian Institute for Theoretical Astrophysics, University of Toronto

Cosmic history: what is U made of?

How Structure in the Universe Arose:

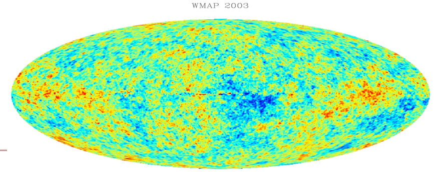
Inflation & the Cosmic Web

CMB & *x*CDM, $x=\Lambda+tilt$,

status@Jan09

is there a y to x?@Jan12

CITA ICAT Canadian Institute for Theoretical Astrophysics L'institut canadien d'astrophysique theorique



WMAP03,06,08

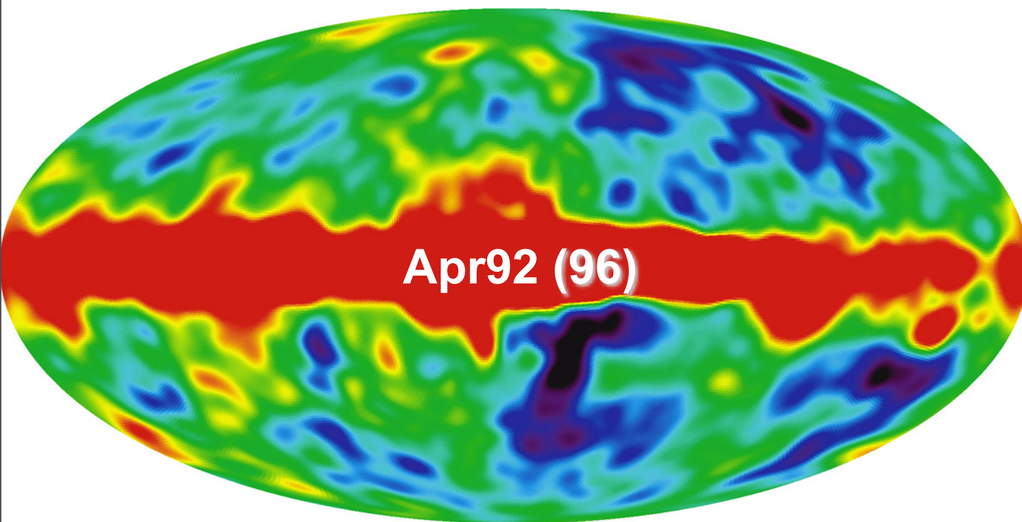
CIAR 25 years cifar

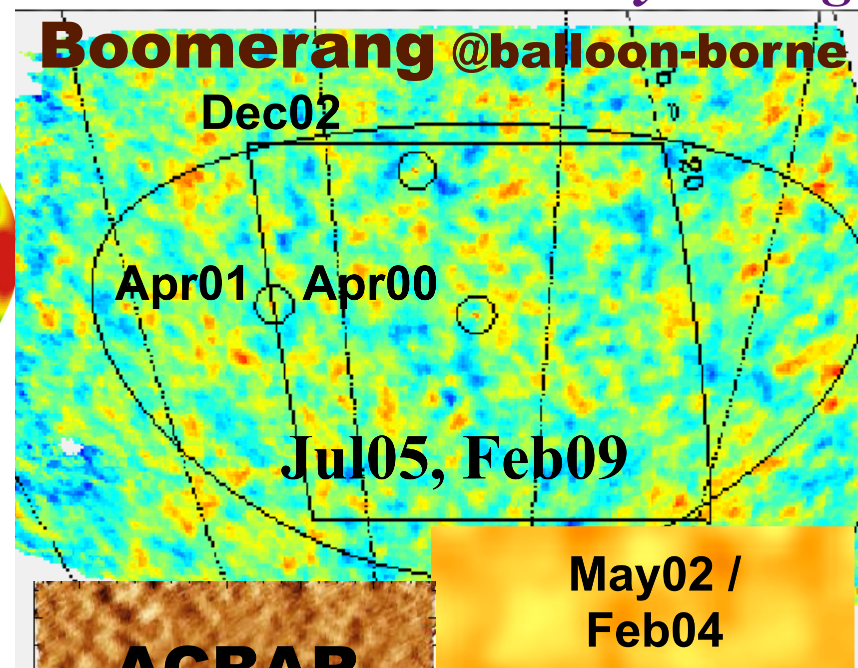
the Cosmology of now & then through first light

Dick Bond Canadian Institute for Theoretical Astrophysics, University of Toronto

COBE Nobel+Gruber 2006

13.65 -0.00038 billion years ago





Cosmic history: what is U made of?

How Structure in the Universe Arose:

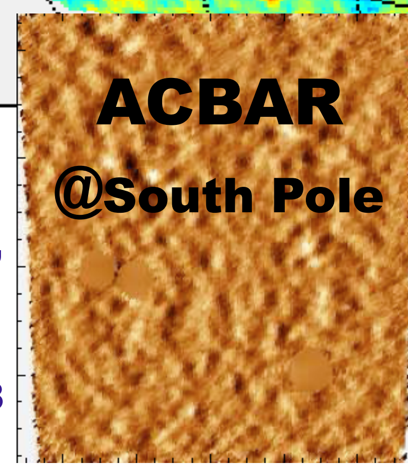
Inflation & the Cosmic Web

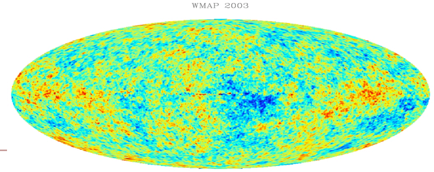
CMB & *x*CDM, *x*=Λ+*tilt*,

status@Jan09

is there a y to x?@Jan12

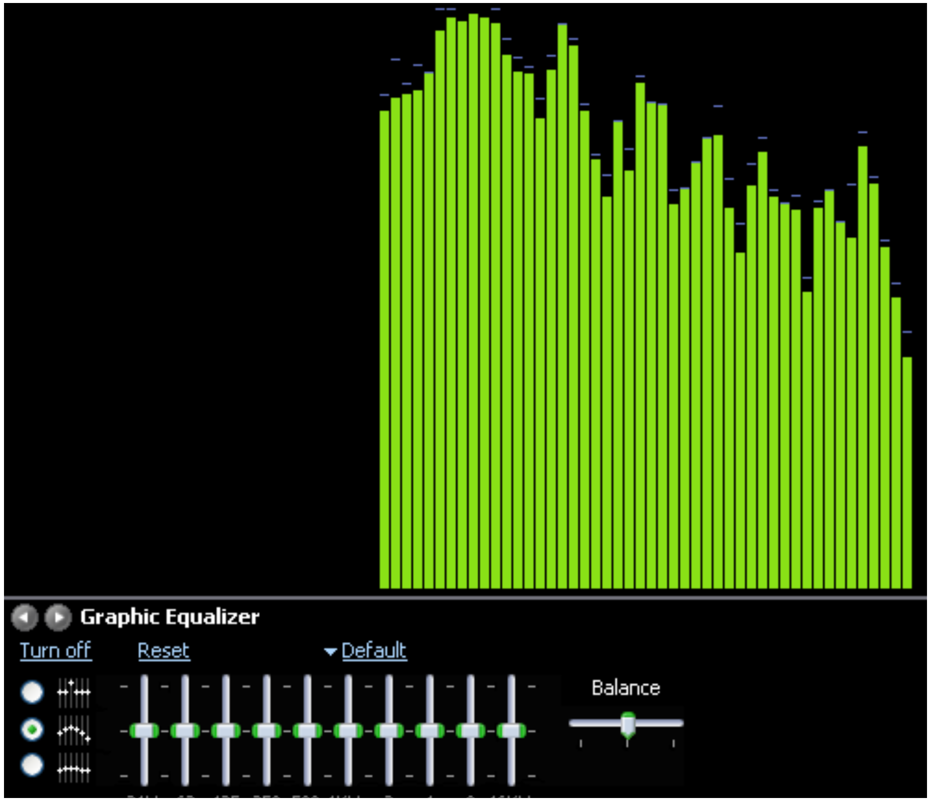
Dec02,
Oct06,
Jan08,
Sept08

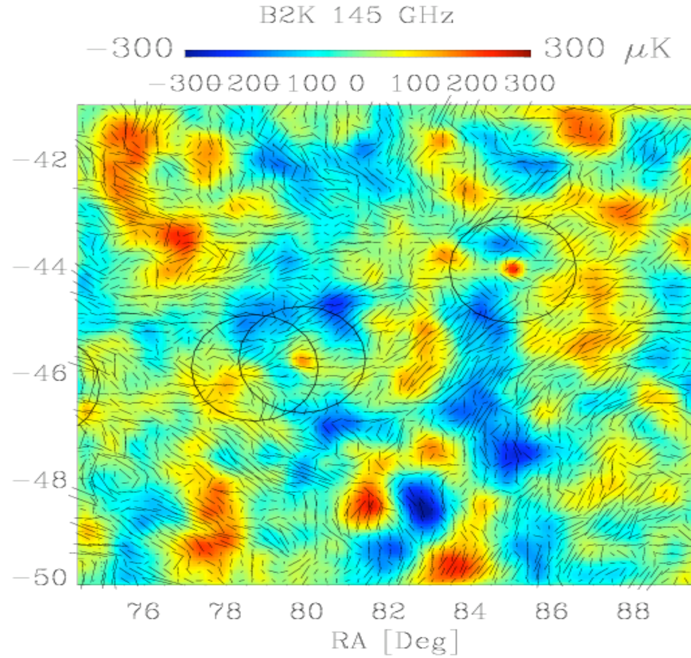


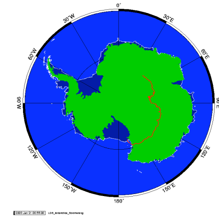


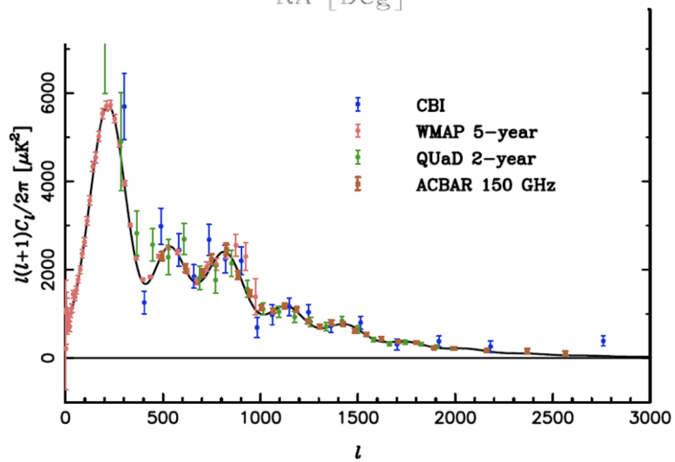
13.65 -0.00038 billion years ago

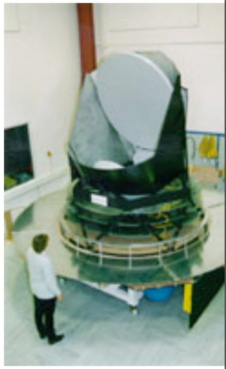
Boom05 deep **Jul05, Feb09**



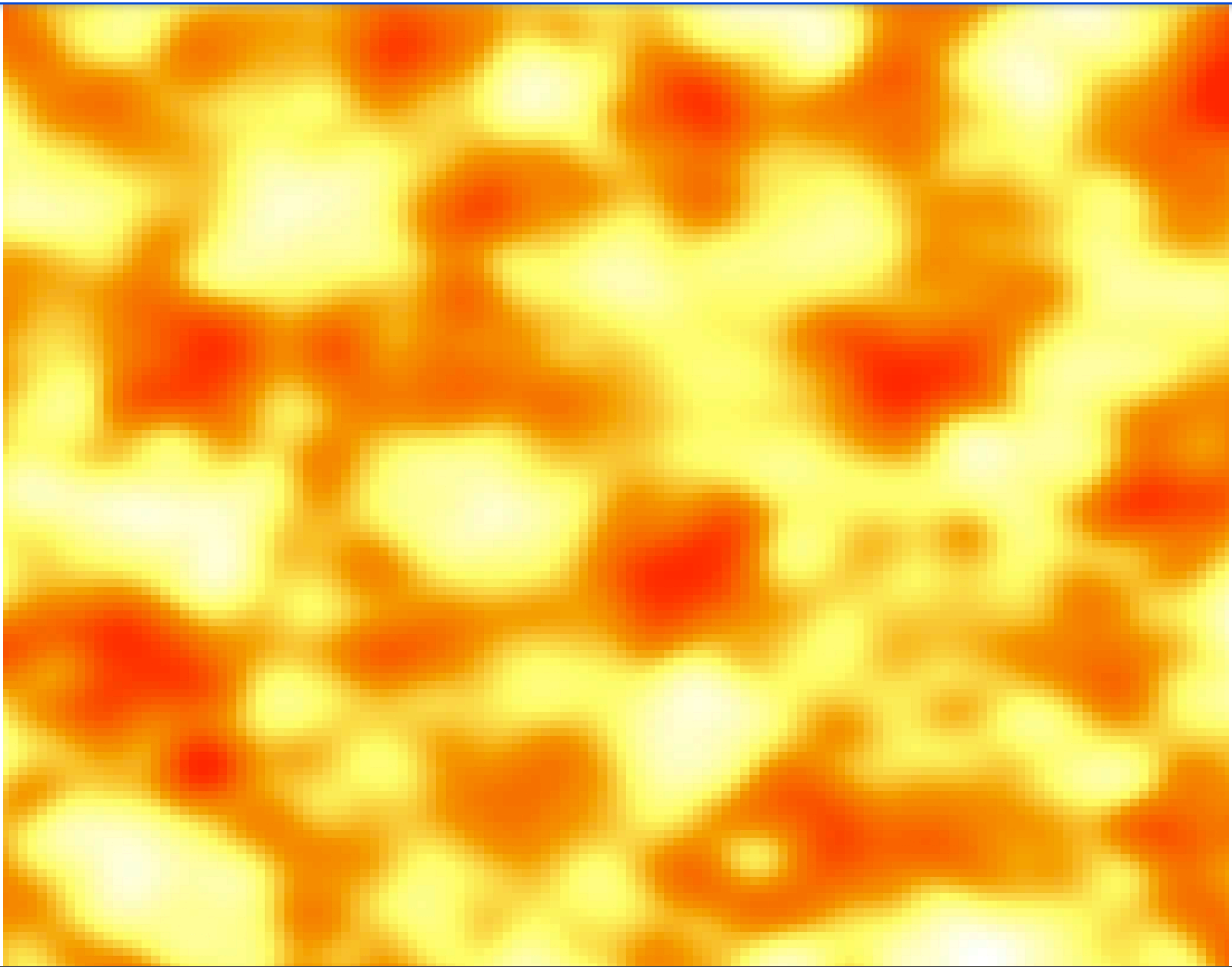




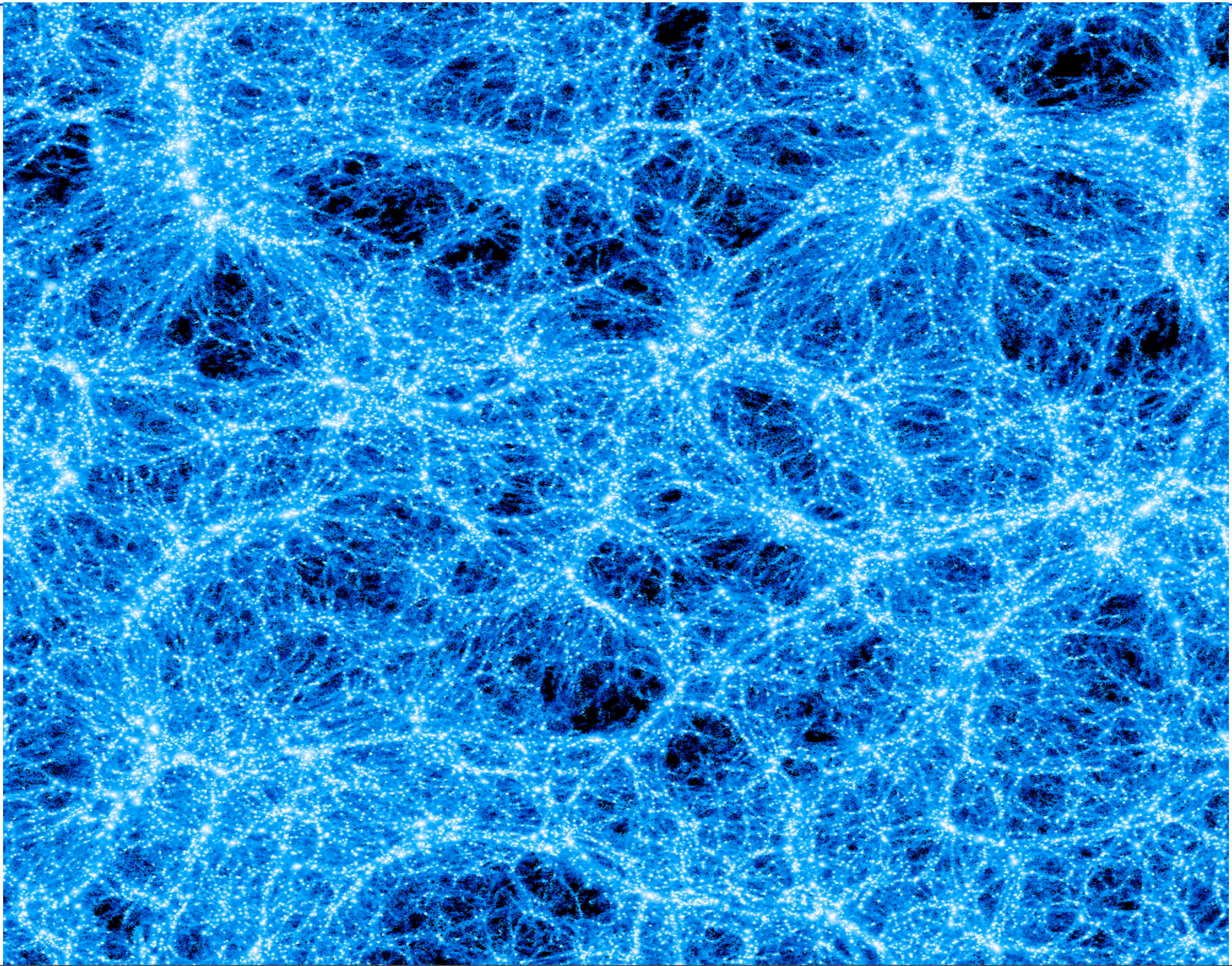




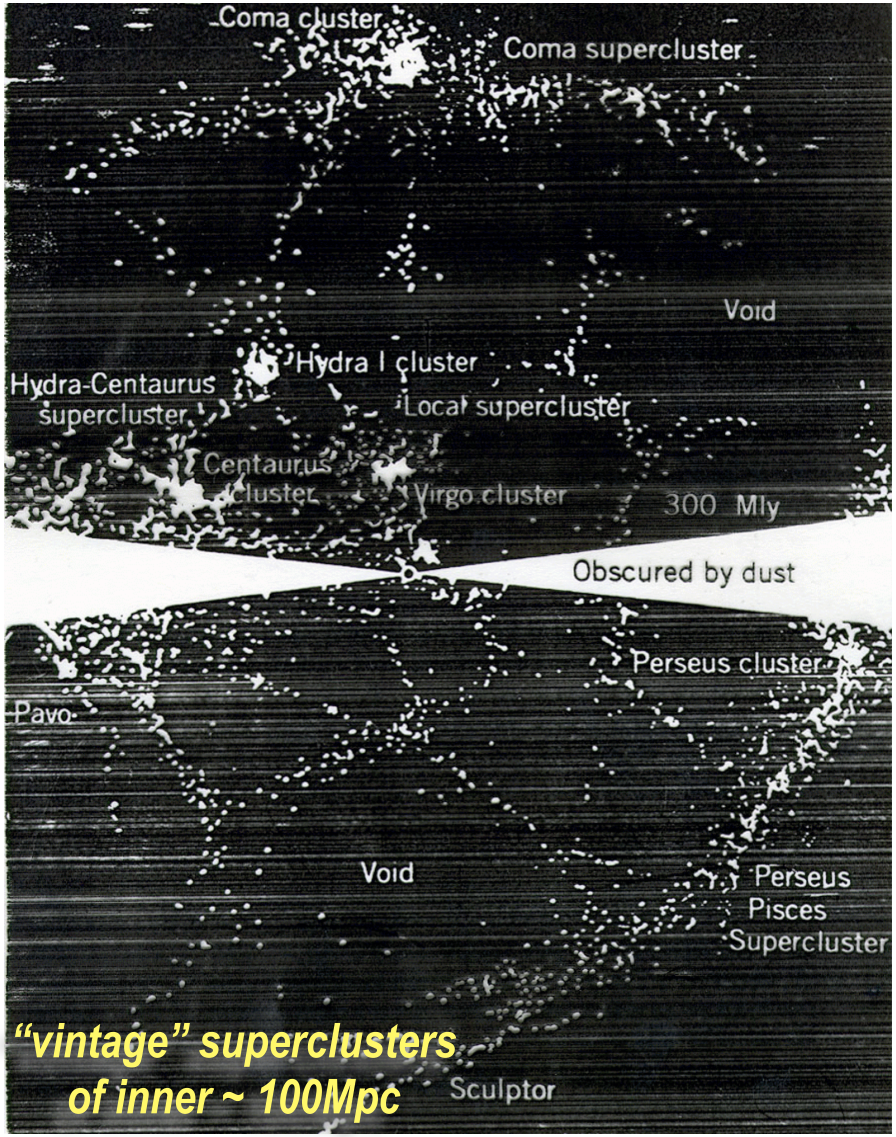
nonlinear Gas & Dark Matter Structure in the Cosmic Web the cluster/gp web “now”, the galaxy/dwarf system “then”

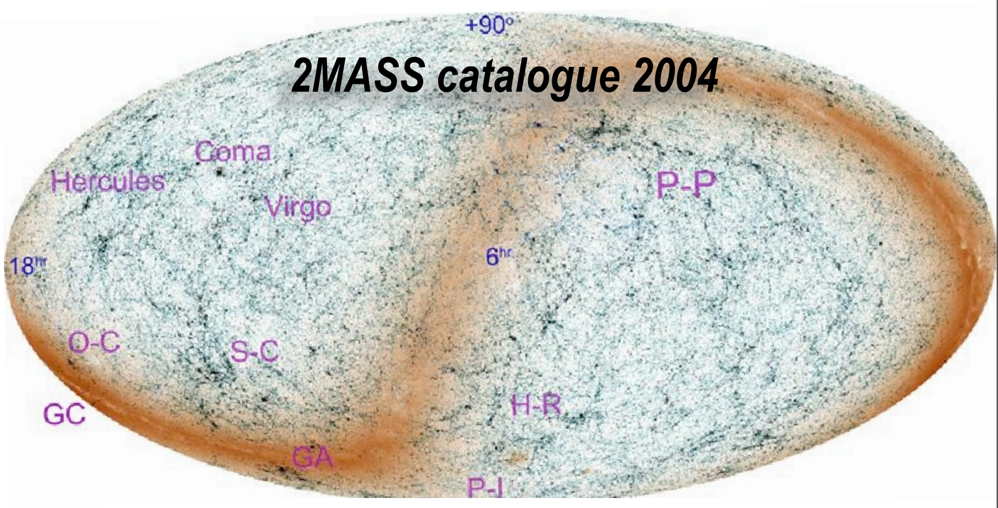


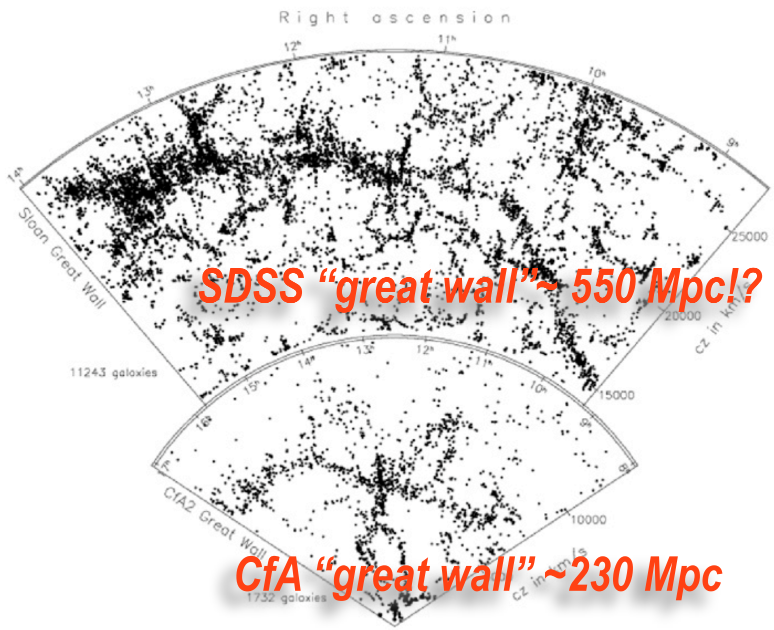
nonlinear Gas & Dark Matter Structure in the Cosmic Web the cluster/gp web “now”, the galaxy/dwarf system “then”

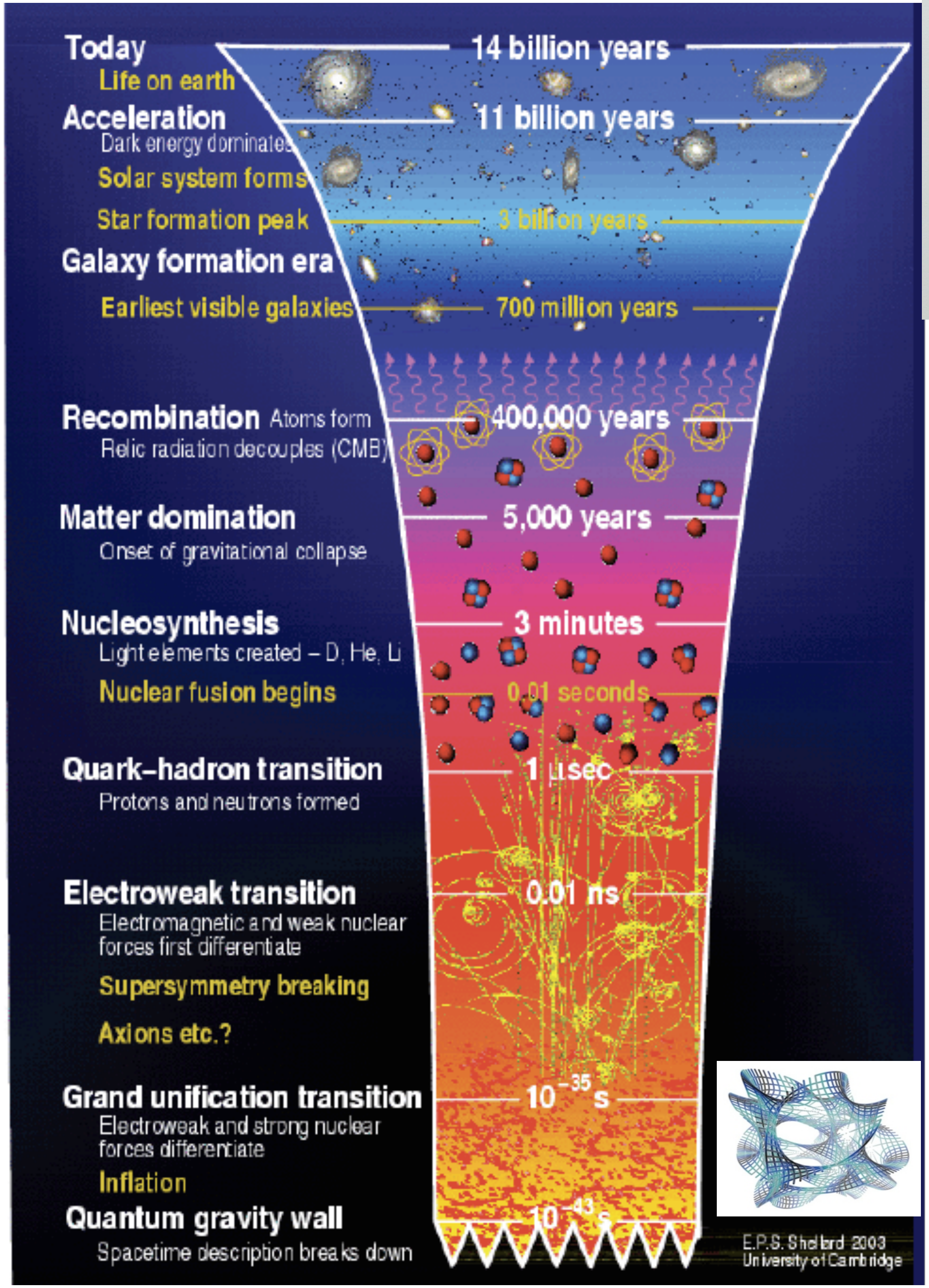


Cosmic Web & Superclustering: a natural consequence of the gravitational instability of a hierarchical Gaussian random density field

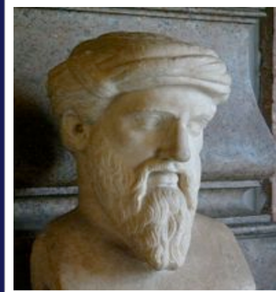




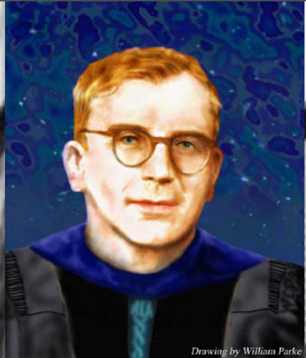


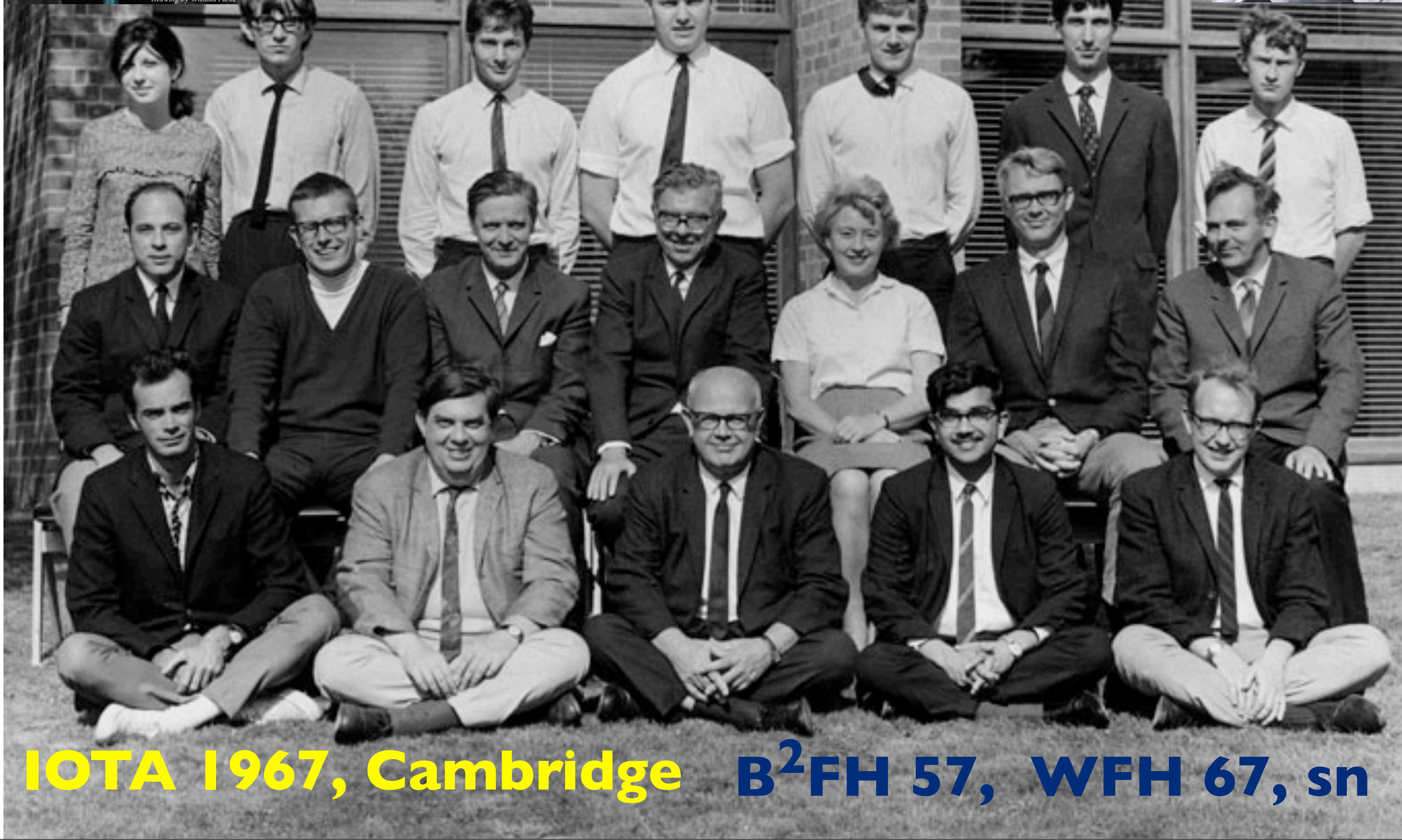


IT from BIT

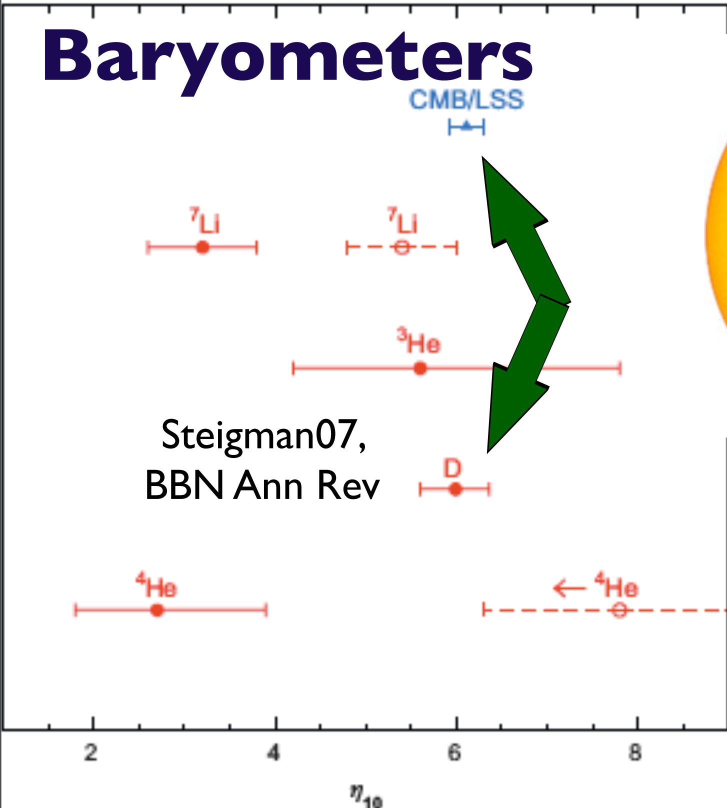


the Meaning may change but the Facts will remain

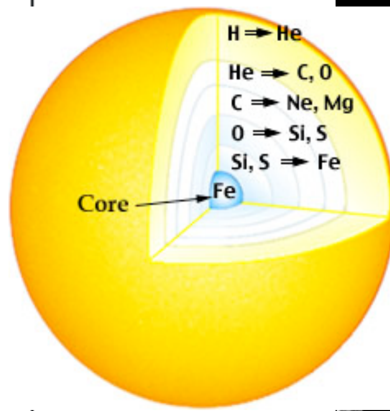

Drawing by William Parke


IOTA 1967, Cambridge
B^2FH 57, WFH 67, sn

Baryometers



Steigman07, BBN Ann Rev



Nobel Prize 84 Willy Fowler + Chandra-sekhar

$$\eta_{10} \equiv 10^{10}(n_B/n_\gamma) \equiv 274\ \Omega_B h^2$$

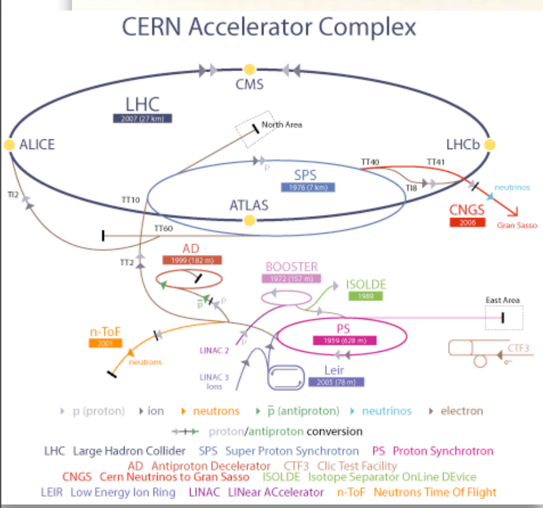
	January 2000	January 2002	June 2002	January 2003	March 2003
$\Omega_b h^2$	$0.0339^{+0.0443}_{-0.0246}$	$0.0222^{+0.0025}_{-0.0021}$	$0.0221^{+0.0024}_{-0.0020}$	$0.0221^{+0.0023}_{-0.0018}$	$0.0233^{+0.0013}_{-0.0013}$

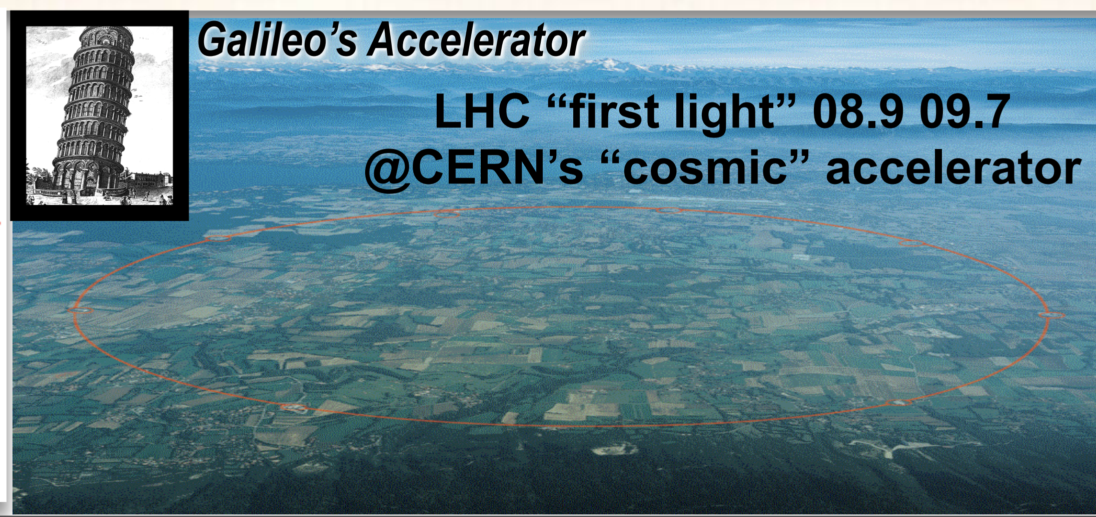
0.0223 ± 0.0007

0.0226 +- 0.0006 wmap3+acbar+cbi+... LSS

0.0233 +- 0.0005 wmap5+acbar+cbi+b03+.+WL+LSS+SN1+Lya

extra-“ordinary” matter



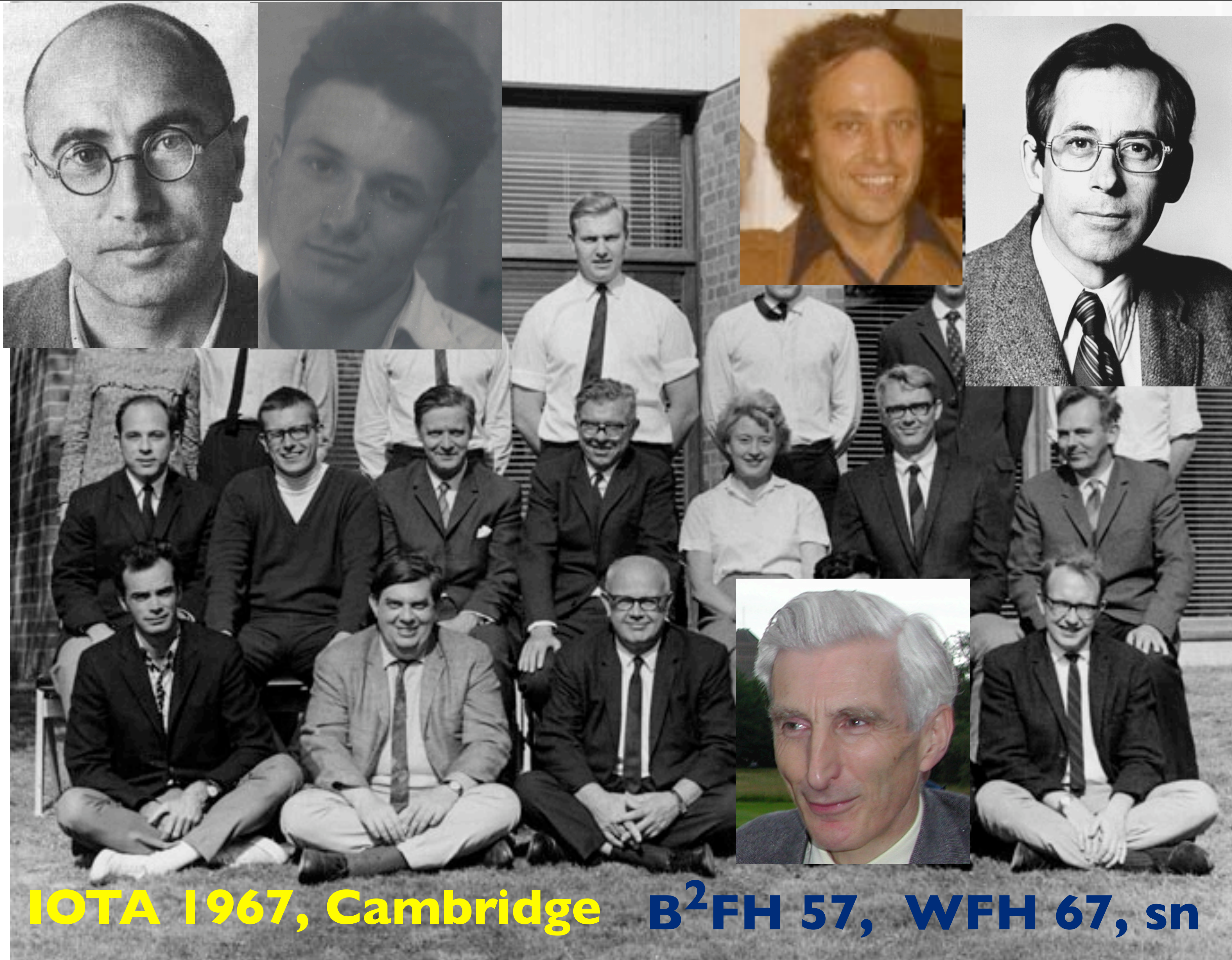


what is mass?

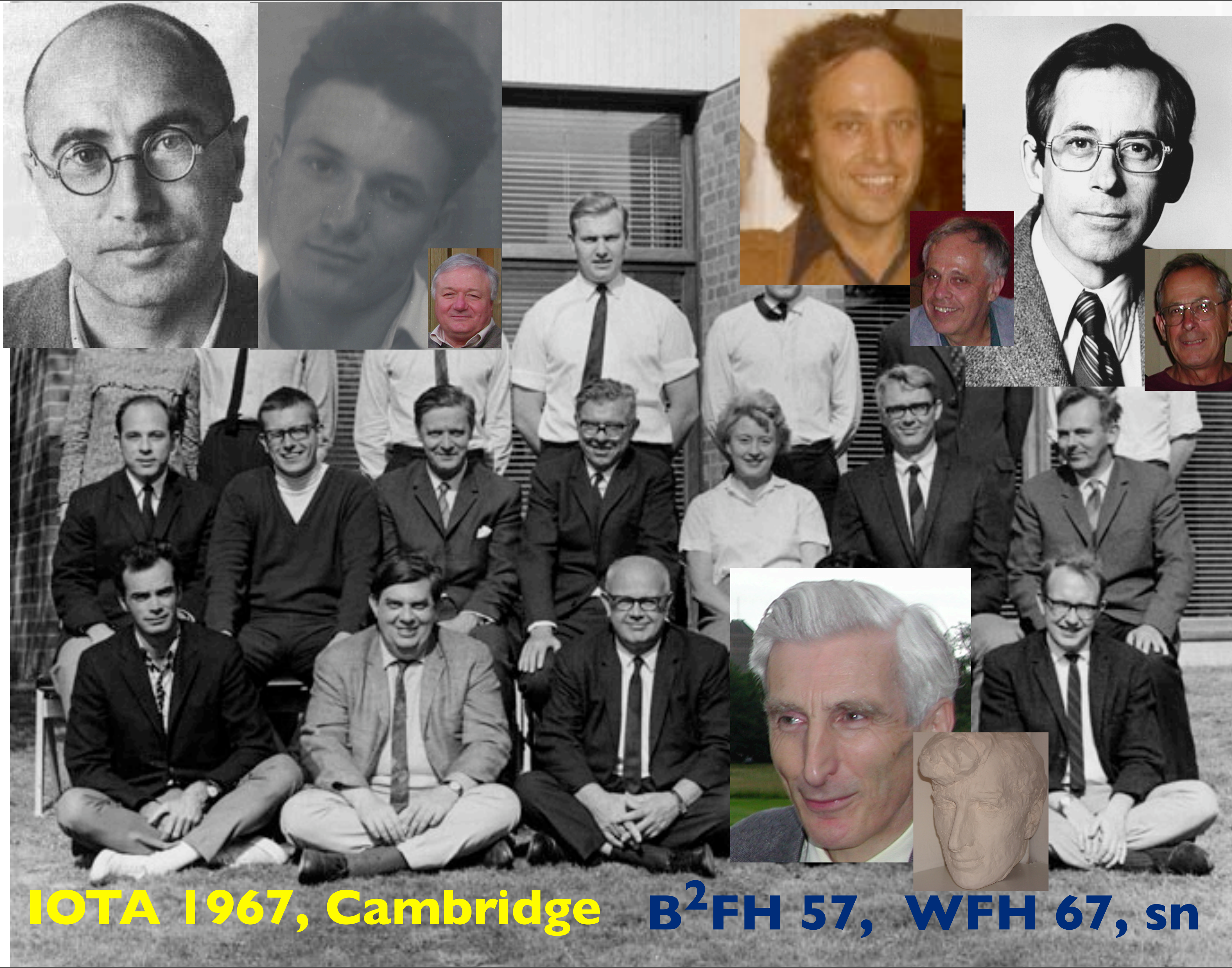
dark matter

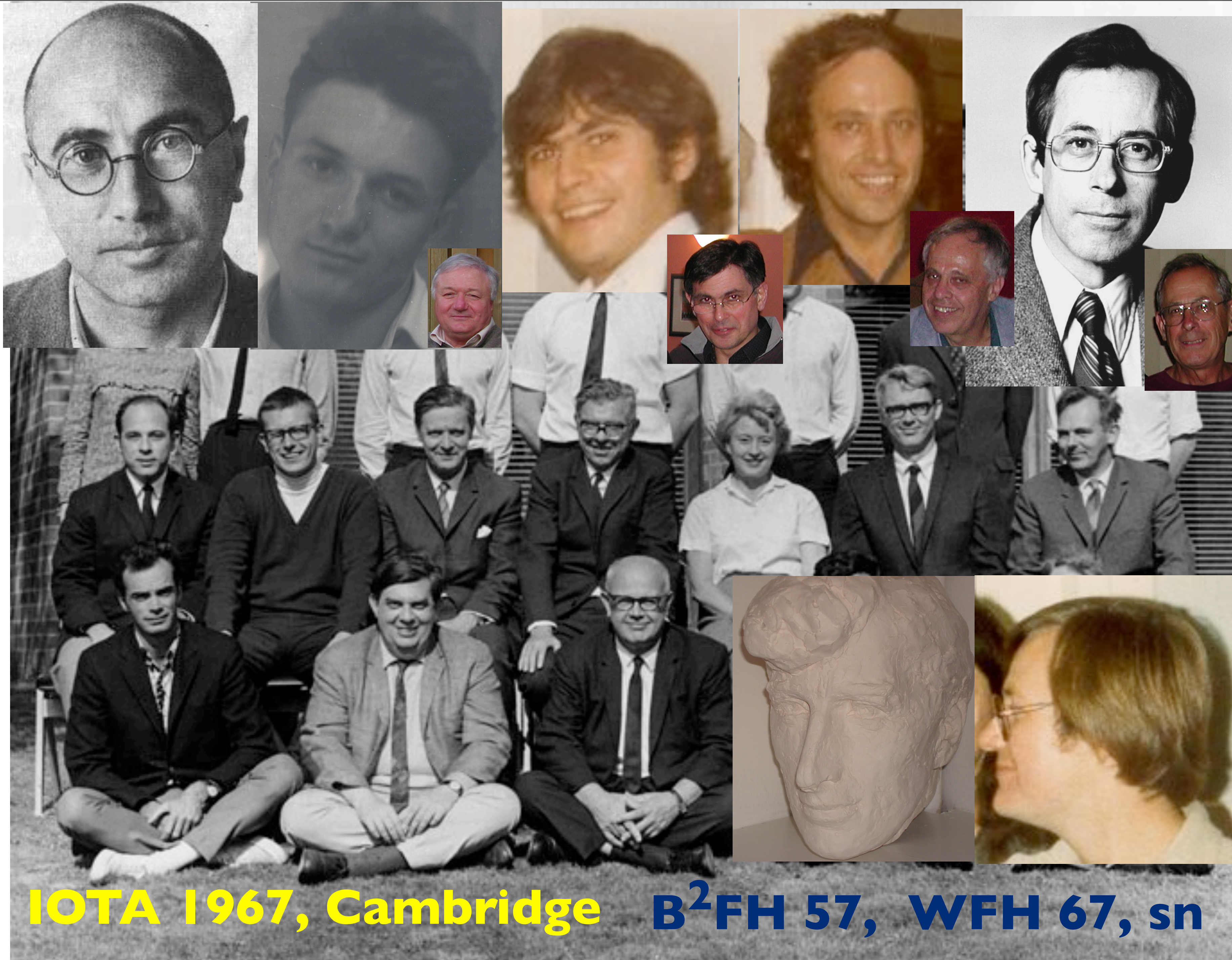
antimatter asymmetry

extra dimensions



IOTA 1967, Cambridge **B^2FH 57, WFH 67, sn**


IOTA 1967, Cambridge
B^{2}FH 57, WFH 67, sn

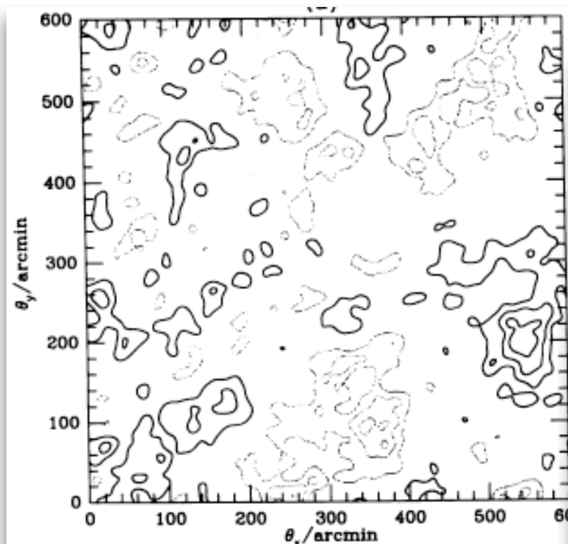

IOTA 1967, Cambridge
B^2FH 57, WFH 67, sn

Delta T over Tea Toronto May 1987: first dedicated CMB conference, exptalists+theorists, primary+secondary ΔT/T

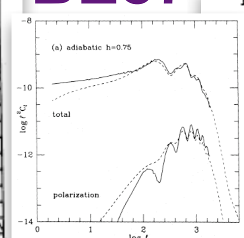
Primary Cosmic Microwave Background Radiation ~ a statistically isotropic all-sky GRF on the 2-sphere $C_L = \langle|\Delta T_{(LM)}|^2\rangle$ with target C_L shapes

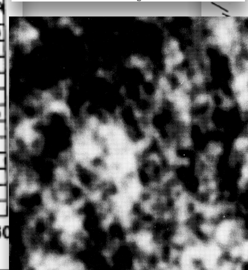
A tentative list of topics organized according to angular scale, with theory and observation intertwined, is:

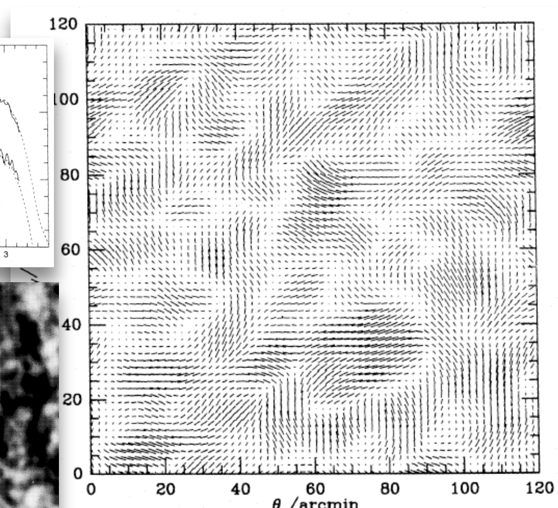
- very small angle anisotropies - VLA results, secondary fluctuations via the Sunyaev-Zeldovich effect, primeval dust emission, and radio sources
- small angle anisotropies - current results, optimal measuring strategies, statistical methods for small signals in larger noise, which universes can we rule out, the reheating issue, future detectors and techniques, CMB map statistics, polarization
- intermediate and large angle anisotropies - $5^o - 10^o$ results, future experiments at $\sim 1^o$, COBE and other large angle analyses, theoretical $C(\theta)'s$ and their angular power spectra, Sachs-Wolfe effect in open Universes, the isocurvature CDM and baryon stories, $\Delta T/T$ from gravitational waves, the cosmic string story.



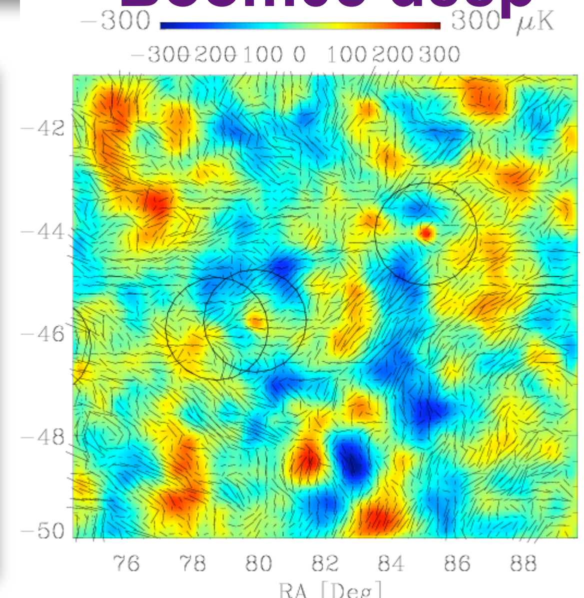
BE87







Boom05 deep



DELTA T OVER TEA WORKSHOP

1-2 May, 1987
Toronto, Canada

Sponsored by
The Canadian Institute for Theoretical Astrophysics and
The Canadian Institute for Advanced Research

Topics

Present and Future Experiments of Cosmic Microwave Background Anisotropies and Their Theoretical Interpretation on very small ($< 1'$), *small* ($1' - 1^o$), *intermediate* ($1^o - 10^o$) *and large* ($> 10^o +$ *multipole*) *angular scales*

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Bitnet BOND@UTORPHYS

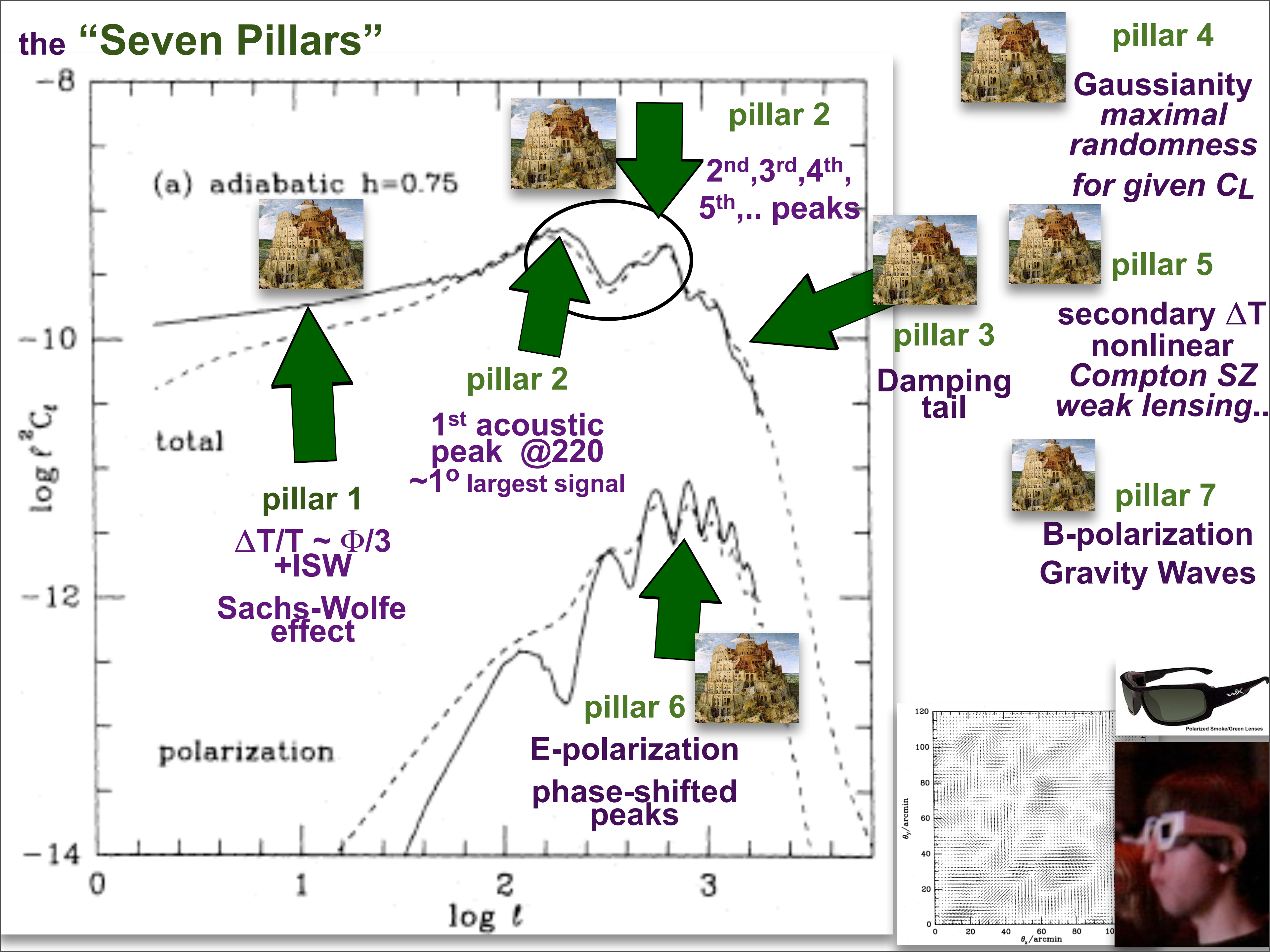
Organizers: J.R. Bond (CITA), D.T. Wilkinson (Princeton)

Delta T over Tea Workshop Participants

Bennett, Chuck, Goddard
Birkinshaw, Marc, Harvard *
Bond, Dick, CITA
Boughn, Steve, Haverford
Boynton, Paul, University of Washington
Cannizzo, John, McMaster
Carlberg, Ray, York
Cheng, Ed, MIT
Couchman, Hugh, CITA
Cottingham, David, Princeton
Daly, Ruth, Boston U
Davies, Rod, Jodrell Bank
Davis, Marc, Berkeley
Dragovan, Marc, Bell Labs
Dyer, Charles, U of Toronto
Efstathiou, George, Cambridge
Fitchett, Mike, CITA
Fomalent, Ed, NRAO
Gorski, Chris, Berkeley
Gulkis, Sam, Caltech
Gush, Herb, UBC
Halpern, Marc, UBC
Ip, Peter, U of Toronto
Juszkiewics, Roman, Berkeley
Henriksen, Dick, Queens
Kaiser, Nick, Cambridge
Kellerman, K, NRAO
Kronberg, Phil, Toronto
Lang, Andrew, Berkeley
Lasenby, Anthony, Cambridge
Lawrence, Charles, Caltech
Lee, Hyung-Mok, CITA
Legg, Tom, Herzberg Institute, Ottawa
Little, Blaine, Toronto
Lubin, Phil, Santa Barbara
Matarrese, Sabino, Padova
Mather, John, Goddard
Meyer, Steve, MIT
Meyers, Steve, Caltech
Moseley, Harvey, Goddard
Nelson, Lorne, CITA
Noriega-Crespo, Alberto, CITA
Occhionero, F., Rome *
Ostriker, Jerry, Princeton
Page, Lyman, MIT
Partridge, Bruce, Haverford
Peterson, J.B., Princeton
Radford, Simon, IRAM, France
Readhead, Tony, Caltech
Richards, Paul, Berkeley
Salopek, Dave, Toronto
Sargent, Wal, Caltech *
Schaeffer, Bob, Goddard
Silk, Joe, Berkeley
Silverberg, Bob, Goddard
Stebbins, Albert, Fermilab
Suto, Yasushi, Berkeley
Timby, Peter, Princeton
Tremaine, Scott, CITA
Timusk, Tom, McMaster
Unruh, Bill, UBC
Vishniac, Ethan, U. Texas Austin
Vittorio, Niccolo, Rome
Wilkinson, Dave, Princeton
Webster, Rachel, Toronto

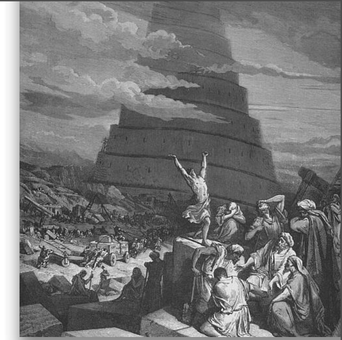
Dave Wilkinson

Wilkinson Microwave Anisotropy Probe



the “Seven Pillars”
pillar 4
Gaussianity
maximal randomness
for given CL
pillar 2
2nd,3rd,4th, 5th,.. peaks
(a) adiabatic h=0.75
pillar 5
secondary ΔT
nonlinear
Compton SZ
weak lensing..
pillar 3
Damping tail
pillar 2
1st acoustic peak @220
~1o largest signal
total
pillar 1
ΔT/T ~ Φ/3
+ISW
Sachs-Wolfe effect
pillar 7
B-polarization
Gravity Waves
pillar 6
E-polarization
phase-shifted peaks
polarization
log ℓ²Cℓ
log ℓ
−8
−10
−12
−14
0
1
2
3
Polarized Smoke/Green Lenses
θy/arcmin
θx/arcmin

COSMIC PARAMETERS THEN



e.g., BBE1987 vary *x* in *x*CDM

for *x*CDM, predict CMB (6deg, 5min); LSS cluster-cluster, cluster-galaxy, bulk flows,

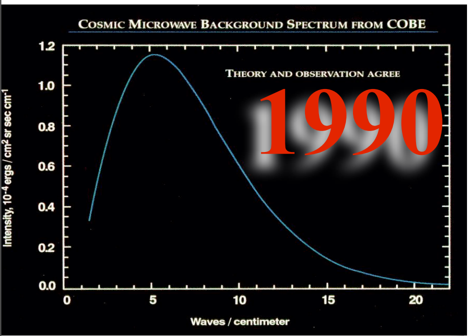
σ_8: redshift of "galaxy formation"

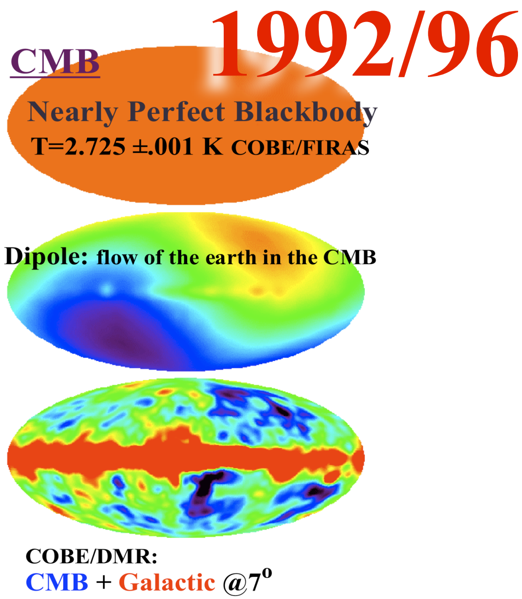
14 Gyr, Ω_Λ=0.8, H0=75, b~c,
50μK cf 30μK cobe, σ_8~0.72

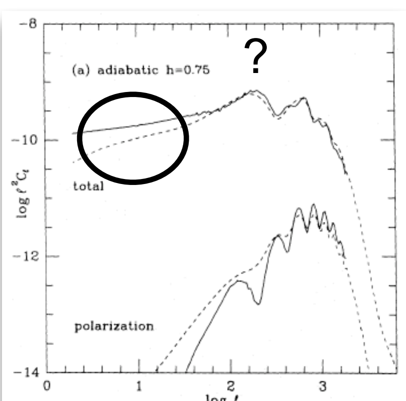
***x*= s /H0 / Λ / Open/ is /is+ad/ h-c/ h+/ b/ b / Λ+b / Op+b /τ /BSI /BSI2**

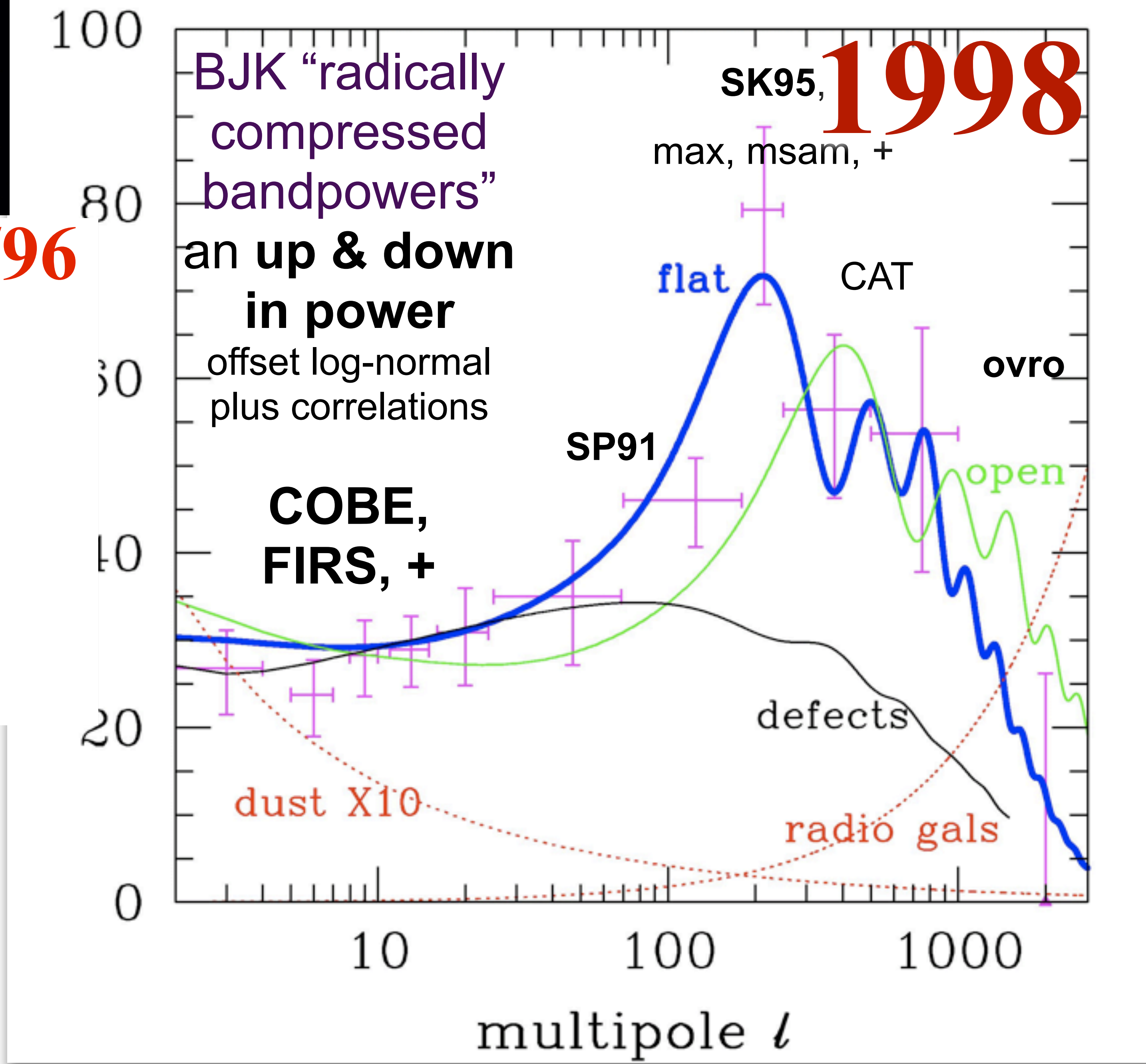
Predictions for Models

Parameter	OBS	CDM	C40	VAC/C	OP/C	ISO/C	ISO/AD	HOT	HC	C + B	B + C	BCV	BCO	CDM + dec	(CDM + X)$_3$ (k_x^{-1} = 300)	(CDM + X)$_2$ (k_x^{-1} = 200)
Ω, Ω_B, H_0	...											1, 0.1, 75				
$\Omega_X(\Omega_\nu)$, Ω_{vac}	...											0.1, 0.8				
b	...											1				
t_0 (by)	GC: 14–22 NC: 13–26											14				
$\sigma_0(R_g = 0.35)$ ...	...											2.4				
z_g	...											1.3				
$\sigma_0(R_{cl} = 5)$	...											0.72				
$\langle v \rangle_c$	...											2.8				
$\xi_{cc}(20)$	1.5											2.2				
$\xi_{cc}(25)$	1.0											1.7				
$\xi_{cc}(30)$	0.72											1.4				
$\xi_{cc}(50)$	0.29											0.59				
$\xi_{cc}(100$	0.08											036				
$\xi_{cg}(20)$	0.49											0.76				
$\xi_{cg}(25)$	0.33											0.54				
$\xi_{cg}(30)$	0.24											0.41				
$\xi_{cg}(40)$	0.14											0.26				
$v(R_f = 3.2)$	610 ± 50											232–1120				
$v(R_f = 15)$	599 ± 104											206–987				
$v(R_f = 25)$												186–894				
$v(R_f = 40)$	970 ± 300											160–771				
$\Delta T/T$ (4.′5)	< 25											10				
$\times 10^6$ (6°)	< 48											25				

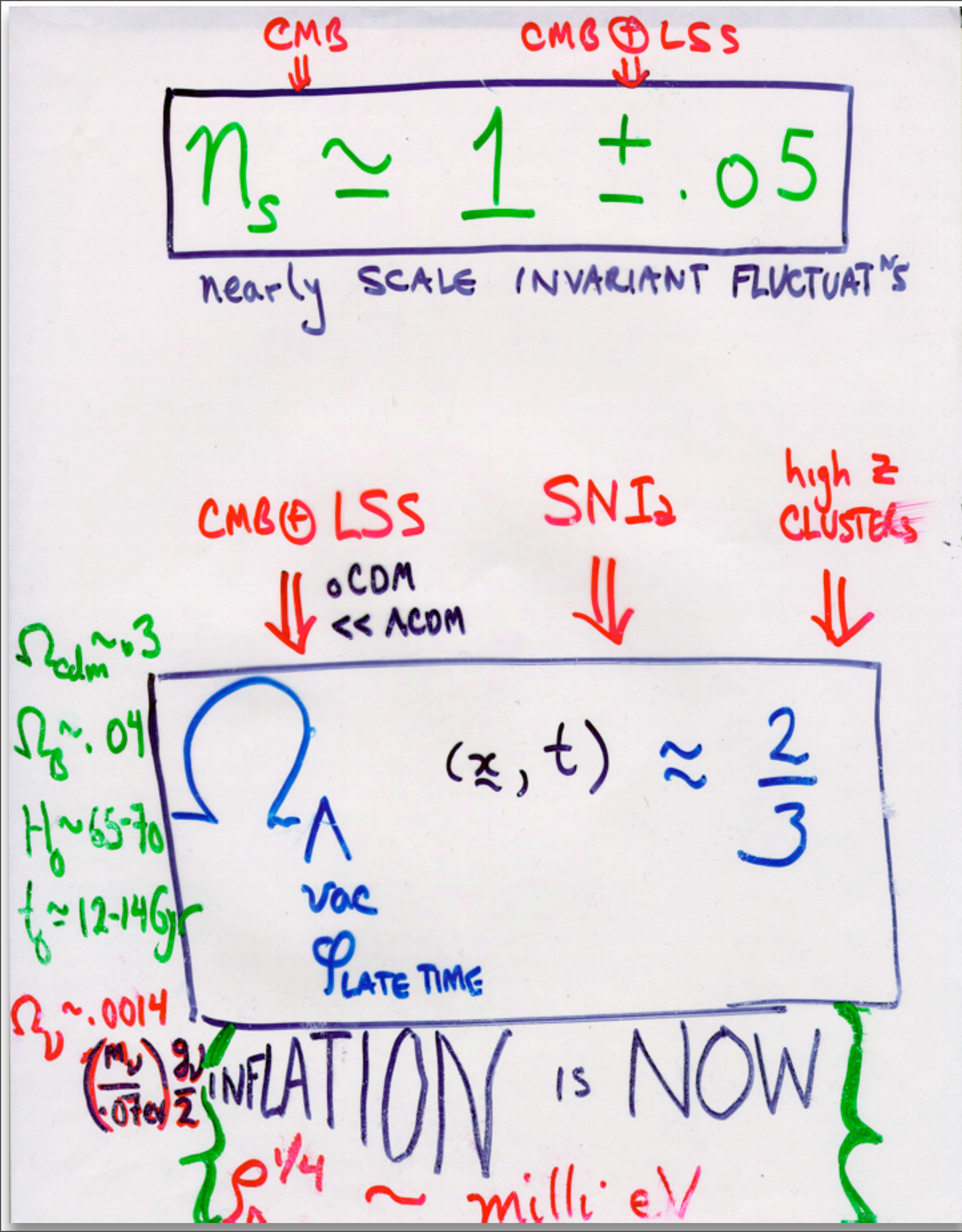

Cosmic Microwave Background Spectrum from COBE
Theory and observation agree
1990
Waves / centimeter
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20


1992/96
CMB
Nearly Perfect Blackbody
T=2.725 ±.001 K COBE/FIRAS
Dipole: flow of the earth in the CMB
COBE/DMR:
CMB + Galactic @7°


(a) adiabatic h=0.75
?
total
polarization
log ℓ
-8
-10
-12
-14
0
1
2
3


1998
BJK "radically compressed bandpowers"
an up & down in power
offset log-normal plus correlations
SK95,
max, msam, +
flat
CAT
ovro
SP91
open
COBE,
FIRS, +
defects
dust X10
radio gals
100
80
20
0
10
100
1000
multipole ℓ

vintage 98 conclusions



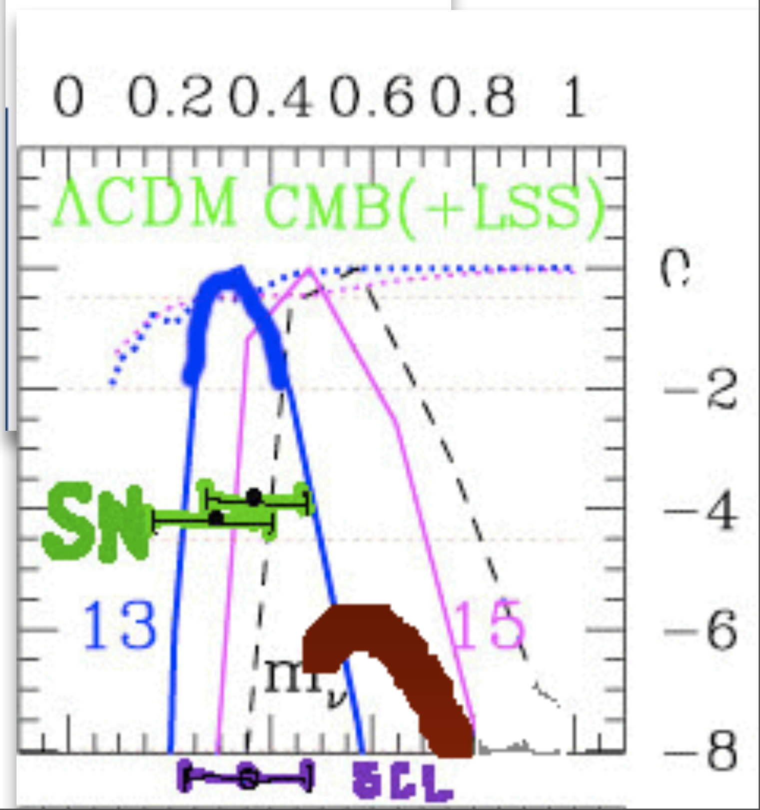
B+Jaffe'96,'98 (13Gyr/t_0)

$\Omega_\Lambda \approx 2/3 \pm .07$ +LSS

$n_s =$

$.98 \pm .07$

$.96 \pm .06$

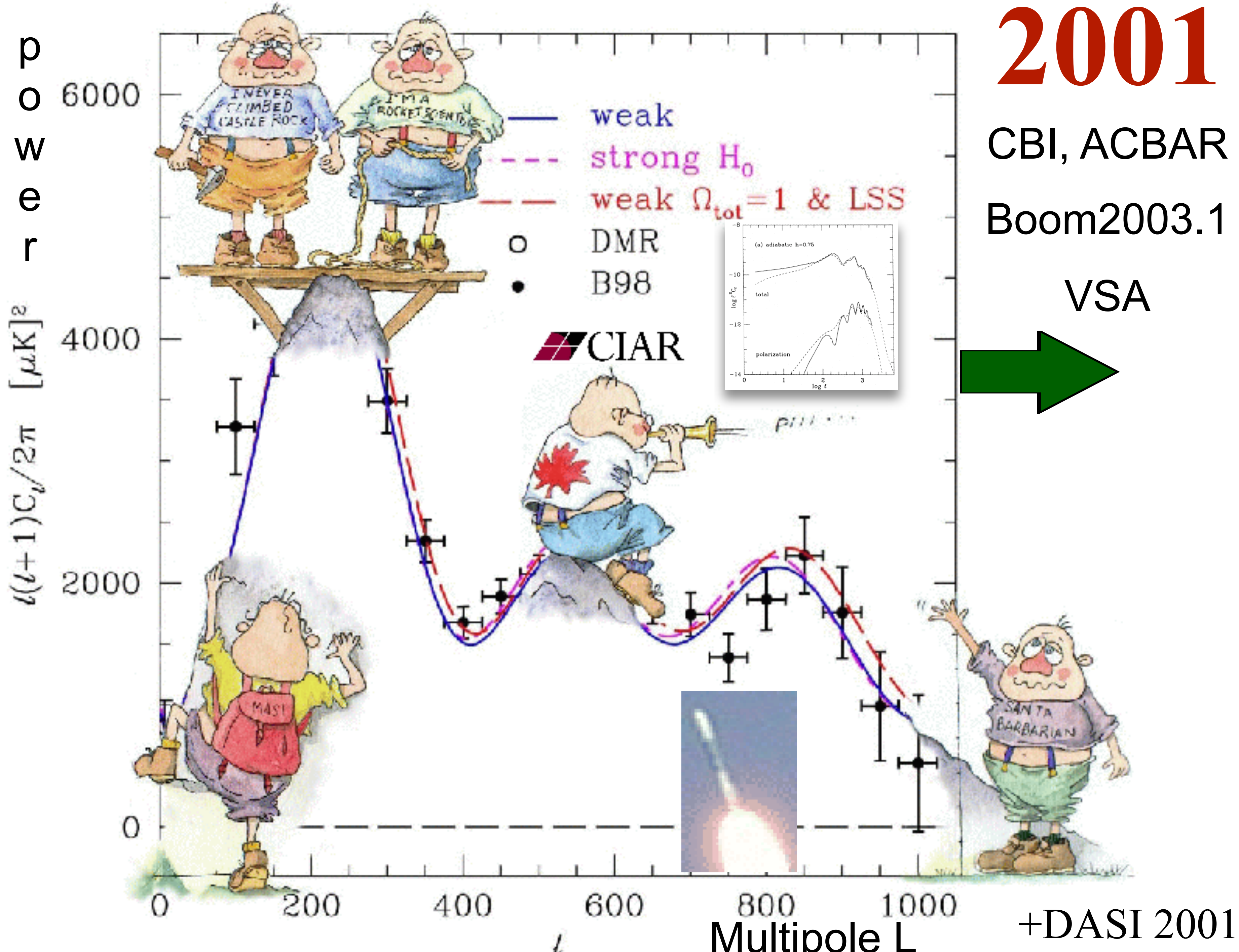


BOOM

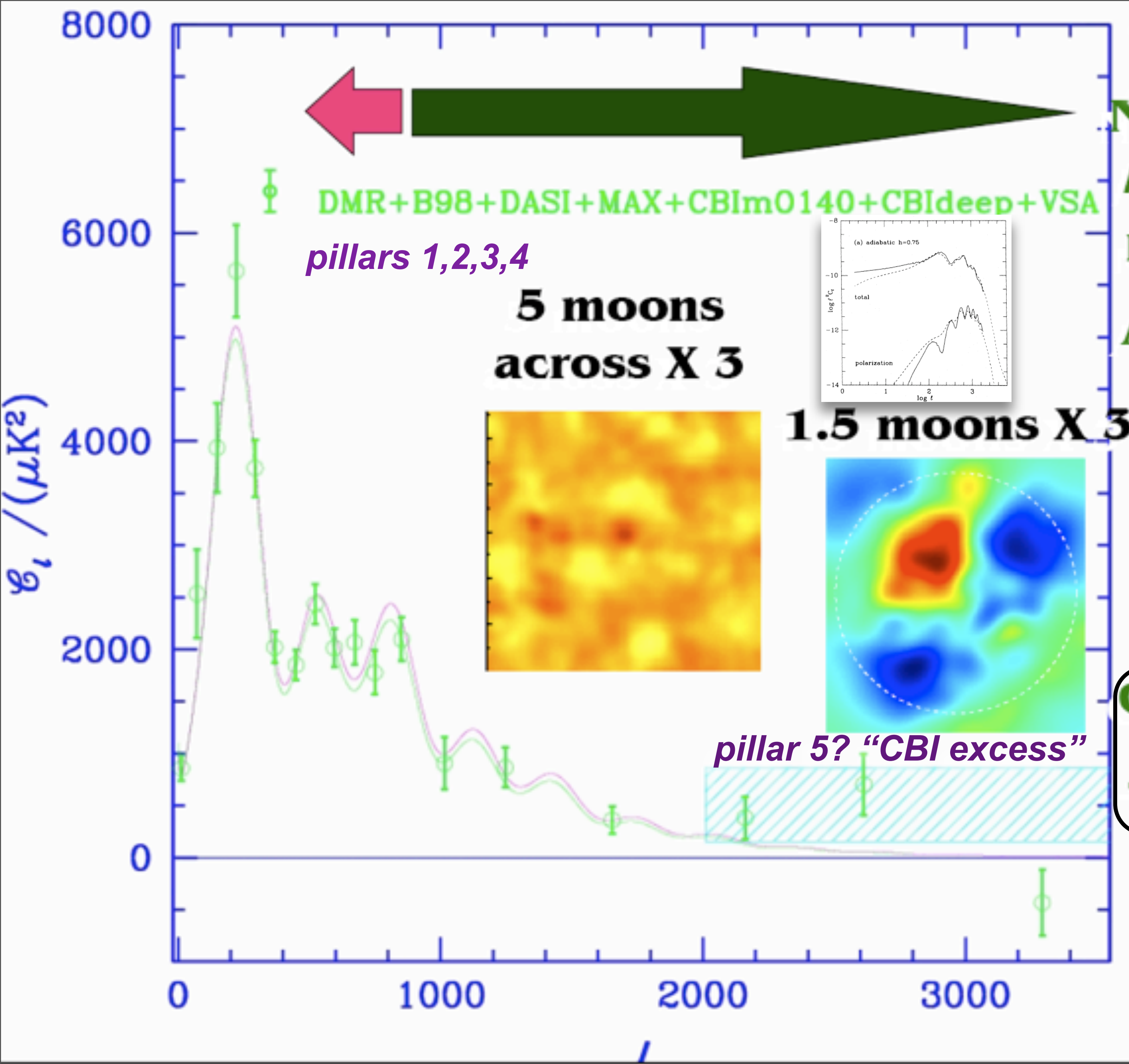
2000

TOCO, Boom test 1999

Maxima 2000



p o w e r
2001
CBI, ACBAR
Boom2003.1
VSA
+DASI 2001
Multipole L
6000
4000
2000
0
0
200
400
600
800
1000
$\ell(\ell+1)C_\ell/2\pi \quad [\mu K]^2$
ℓ
weak
strong H_0
weak $\Omega_{tot}=1$ & LSS
DMR
B98
CIAR
I NEVER CLIMBED CASTLE ROCK
I'M A ROCKET SCIENTIST
MASI
SANTA BARBARIAN
(a) adiabatic h=0.75
total
polarization



2002

NSF/Caltech /CITA/CIAR

May 23,2002

AAS Jun02

Grand unified spectrum

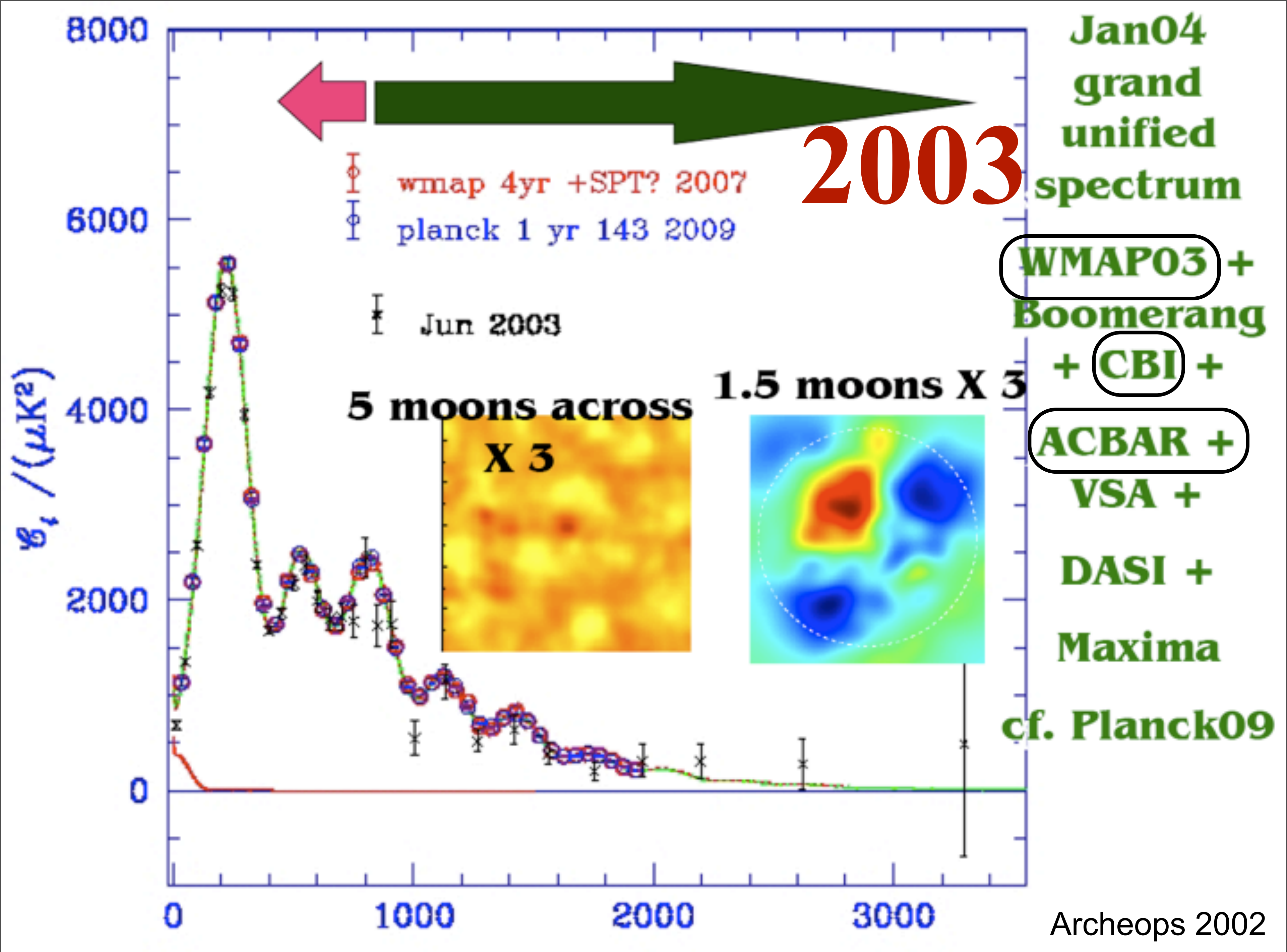
Adds

CBI mosaic

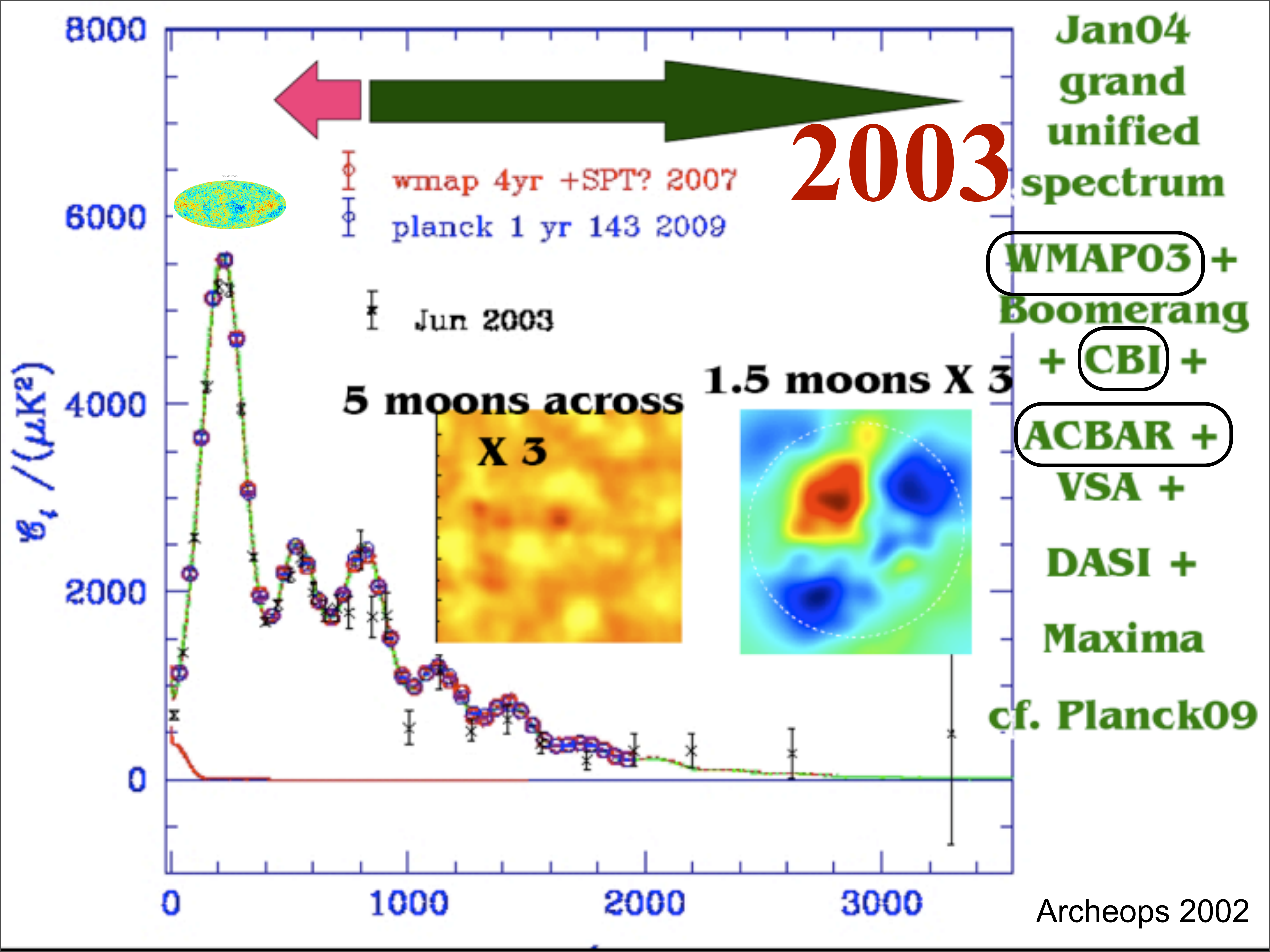
+CBI deep

+VSA

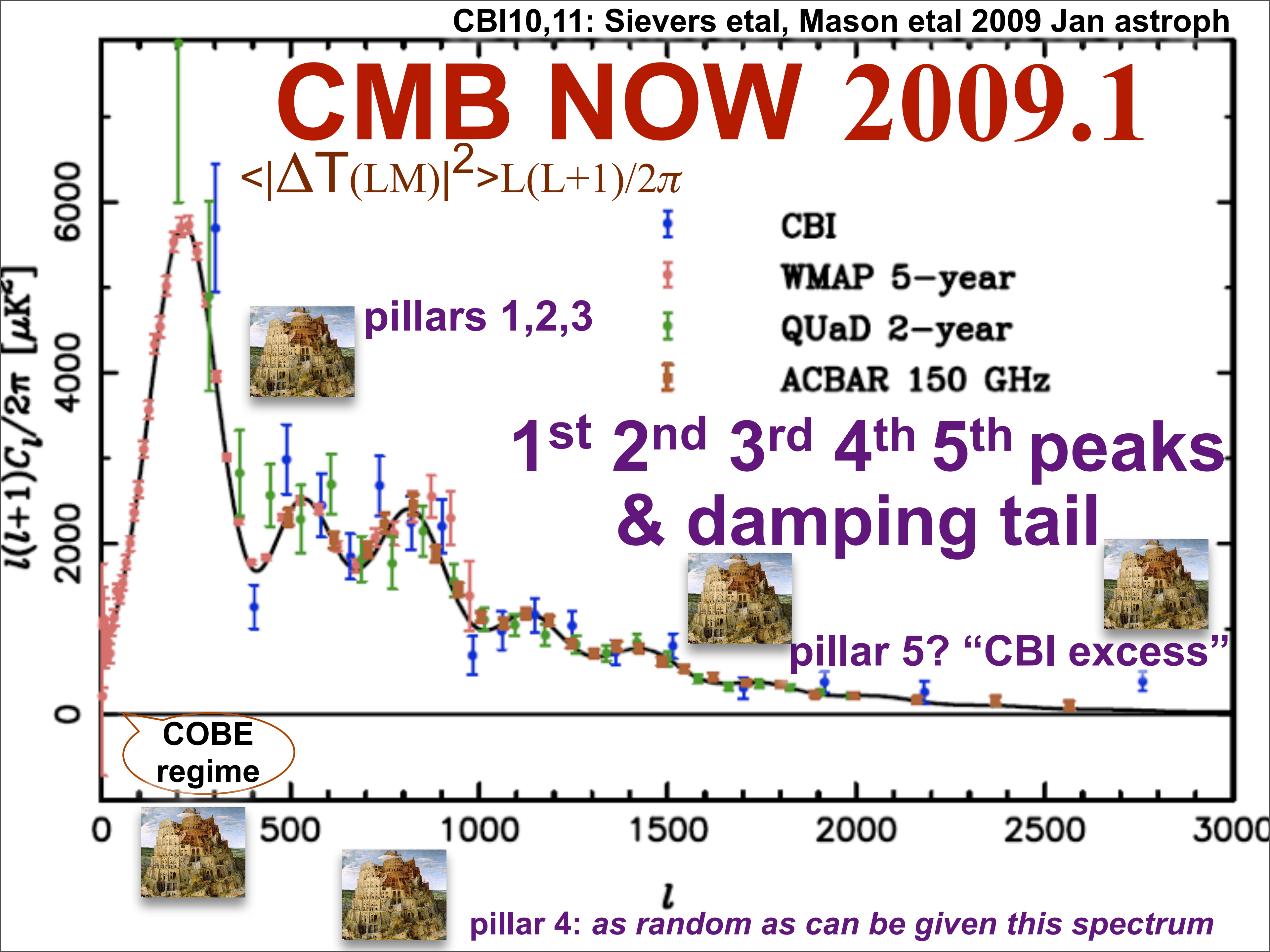

WMAP
launch
2001.6
Text
Dave Wilkinson
Rashid Sunyaev

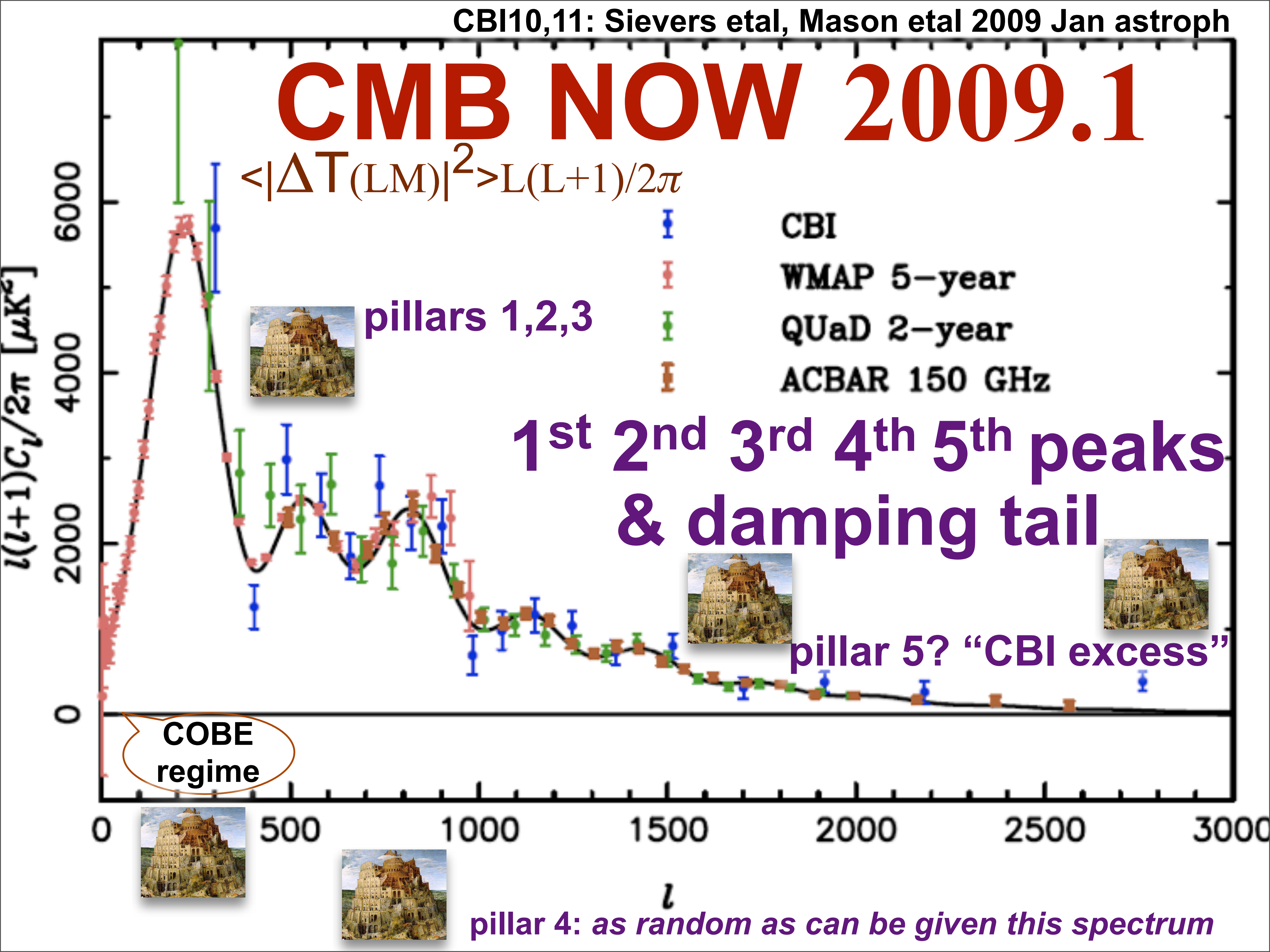


8000
6000
4000
2000
0
0
1000
2000
3000
$\mathcal{C}_\ell$ /(μK²)
wmap 4yr +SPT? 2007
planck 1 yr 143 2009
Jun 2003
2003
5 moons across
X 3
1.5 moons X 3
Jan04 grand unified spectrum
WMAP03 +
Boomerang
+ CBI +
ACBAR +
VSA +
DASI +
Maxima
cf. Planck09
Archeops 2002



2003
wmap 4yr +SPT? 2007
planck 1 yr 143 2009
Jun 2003
5 moons across
X 3
1.5 moons X 3
Jan04
grand
unified
spectrum
WMAP03 +
Boomerang
+ CBI +
ACBAR +
VSA +
DASI +
Maxima
cf. Planck09
Archeops 2002


CBI10,11: Sievers etal, Mason etal 2009 Jan astroph
CMB NOW 2009.1
<|ΔT(LM)|2>L(L+1)/2π
CBI
WMAP 5-year
QUaD 2-year
ACBAR 150 GHz
pillars 1,2,3
1st 2nd 3rd 4th 5th peaks
& damping tail
pillar 5? "CBI excess"
COBE regime
pillar 4: as random as can be given this spectrum
l(l+1)C_l/2π [μK²]
0
2000
4000
6000
0
500
1000
1500
2000
2500
3000
l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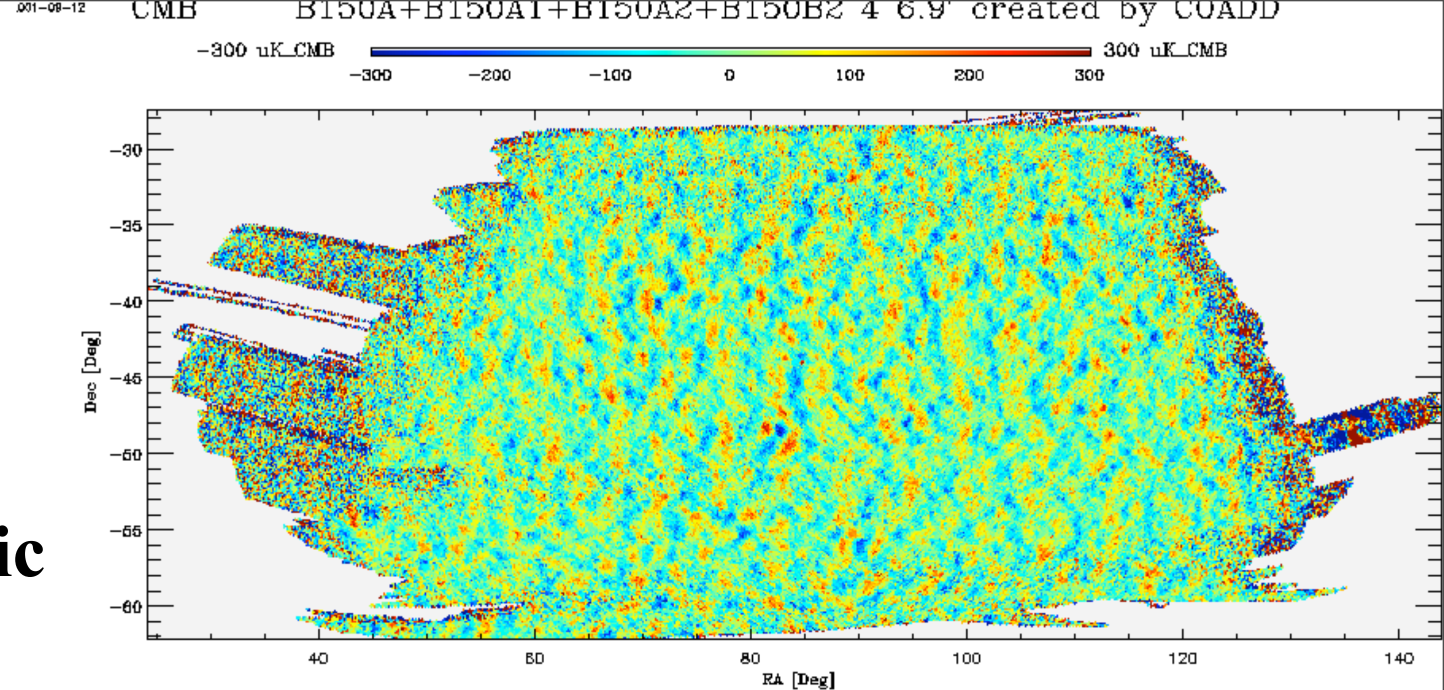
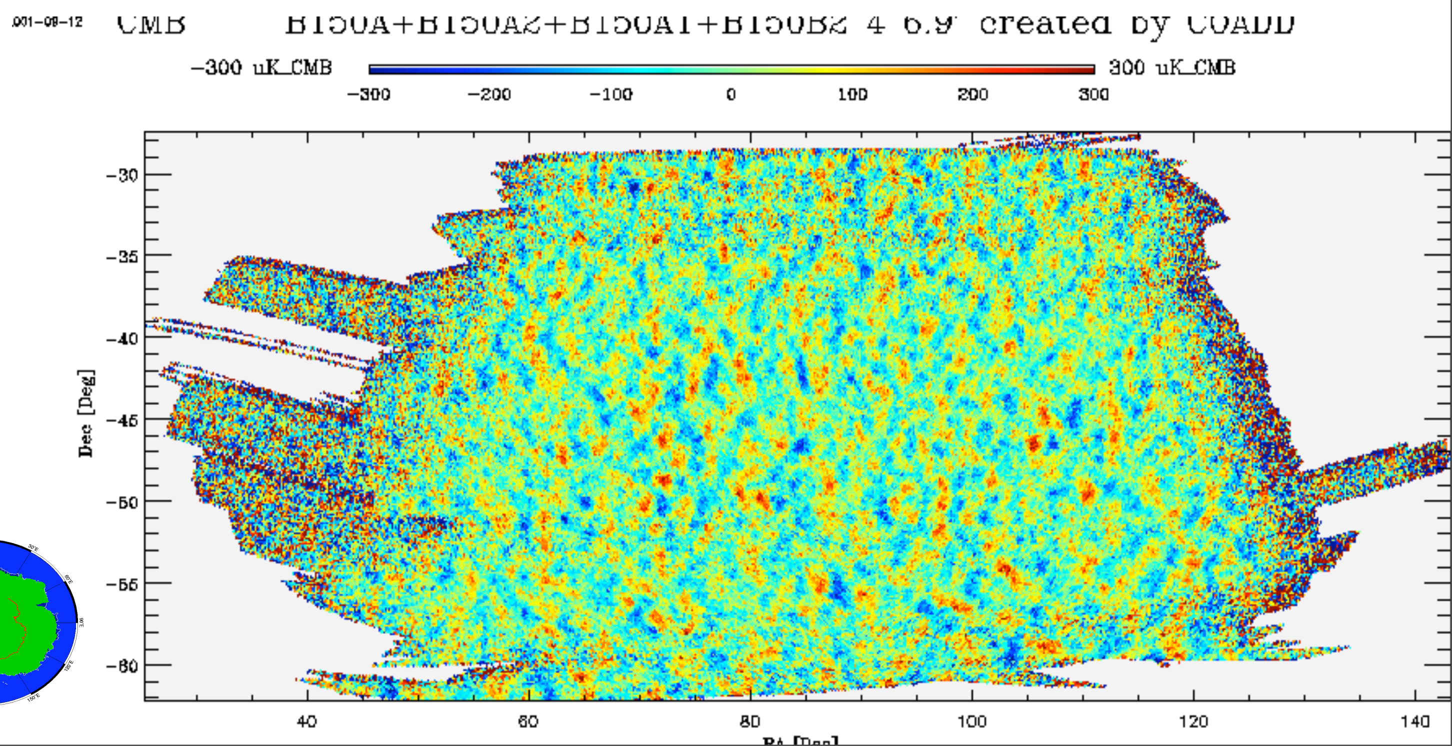
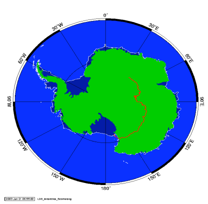
l(l+1)C_l/2π [μK²]
0
2000
4000
6000
0
500
1000
1500
2000
2500
3000
l

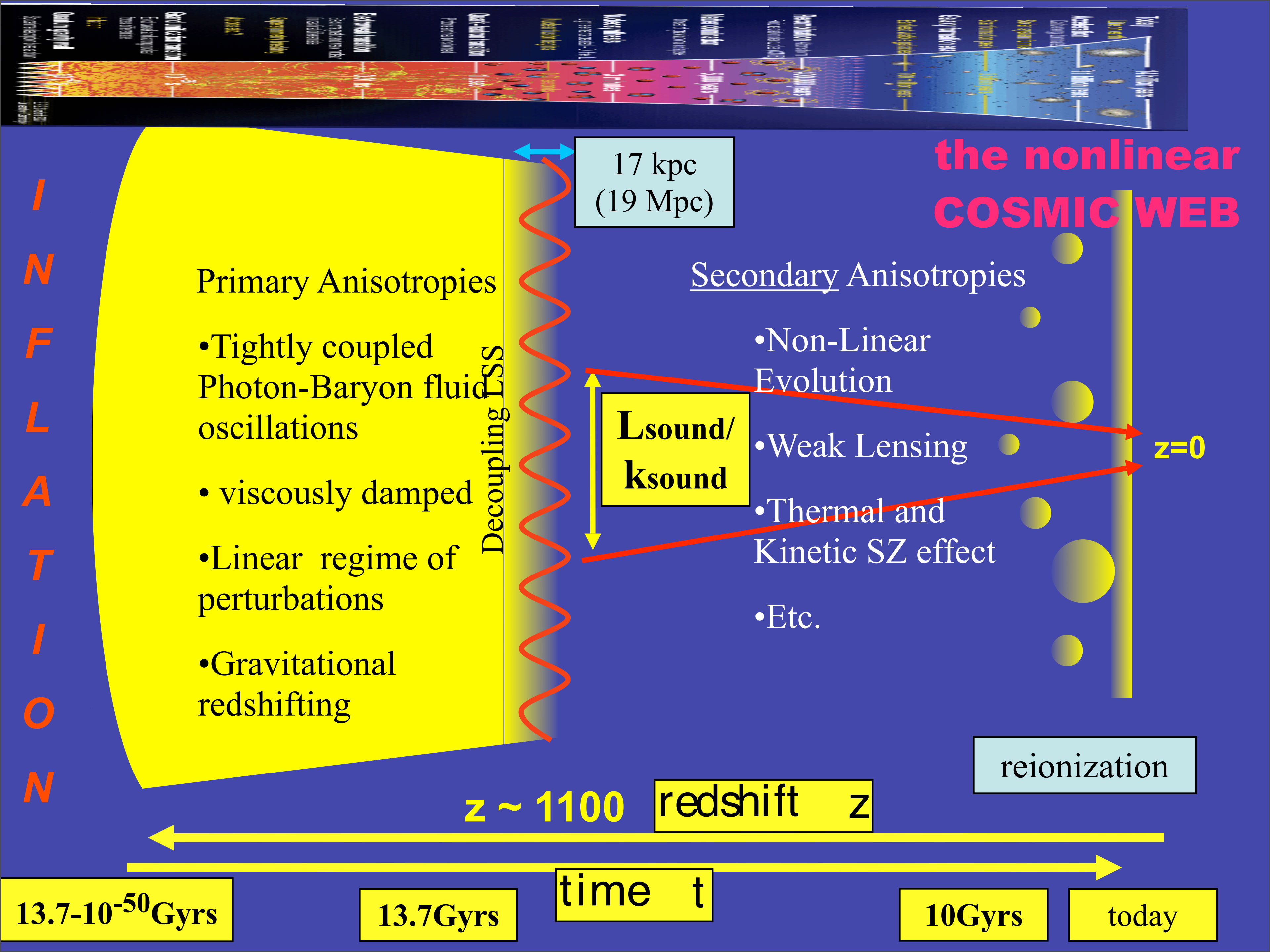
Boomerang @150GHz is (nearly) Gaussian: Simulated vs Real

thermodynamic CMB temperature fluctuations 2.9% of sky ΔT~30 ppm







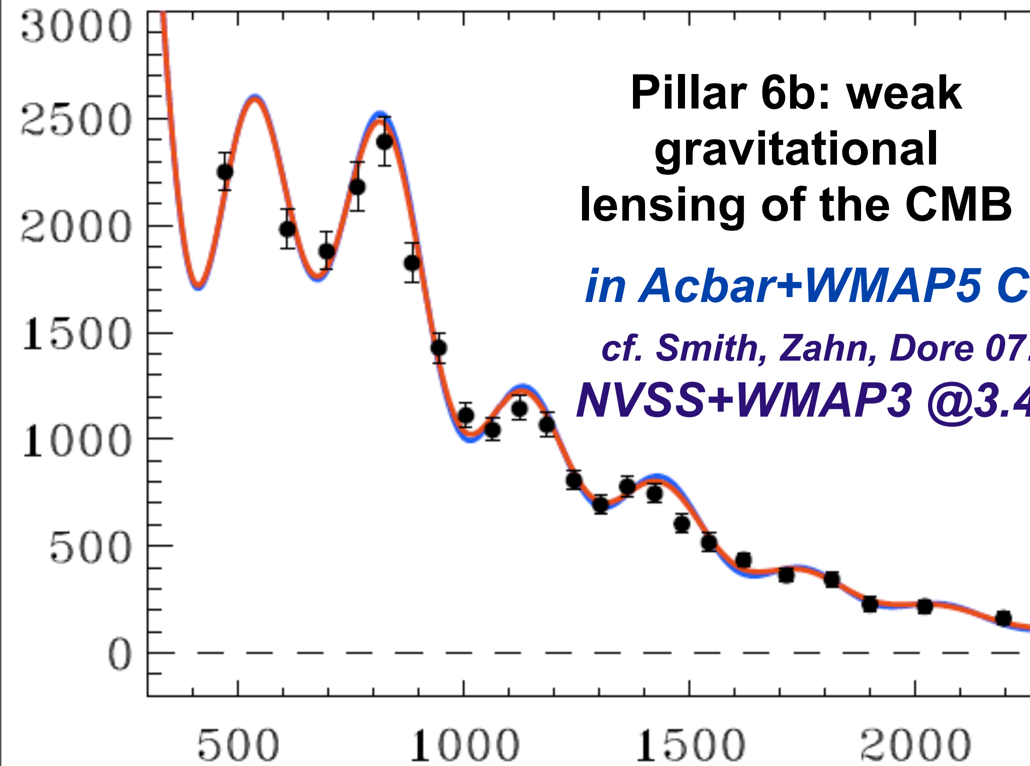


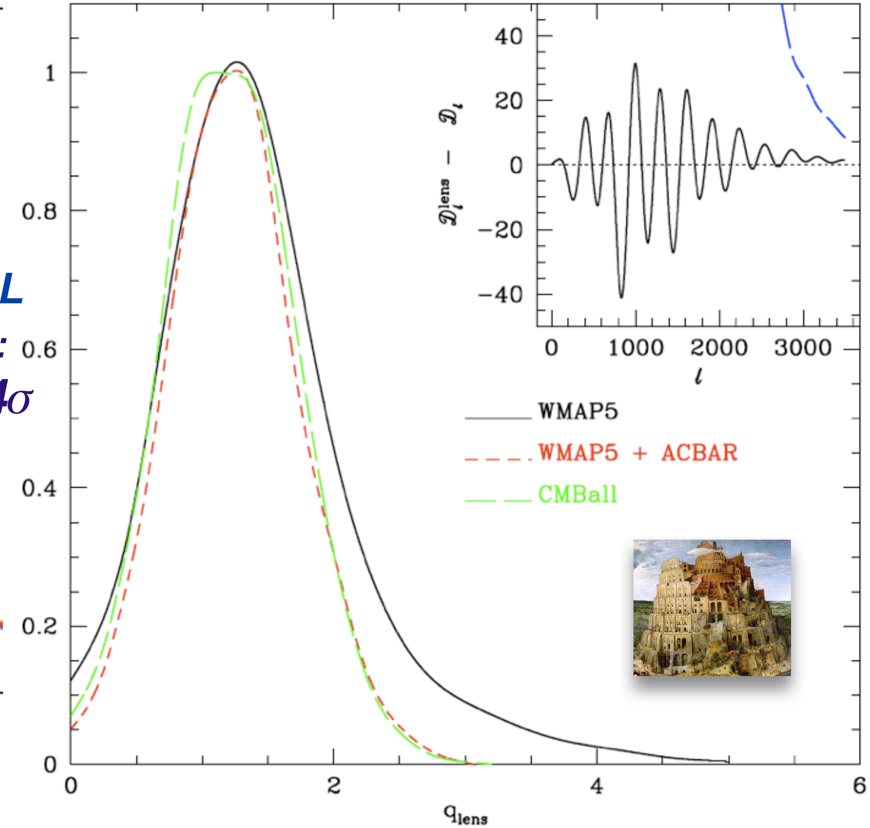
the nonlinear
COSMIC WEB
17 kpc
(19 Mpc)
INFLATION
Primary Anisotropies
•Tightly coupled Photon-Baryon fluid oscillations
• viscously damped
•Linear regime of perturbations
•Gravitational redshifting
Decoupling LSS
Lsound/
ksound
Secondary Anisotropies
•Non-Linear Evolution
•Weak Lensing
•Thermal and Kinetic SZ effect
•Etc.
z=0
reionization
z ~ 1100
redshift z
time t
13.7-10^-50Gyrs
13.7Gyrs
10Gyrs
today

Pillar 6b: weak gravitational lensing of the CMB

in Acbar+WMAP5 C_L

cf. Smith, Zahn, Dore 07: NVSS+WMAP3 @3.4σ

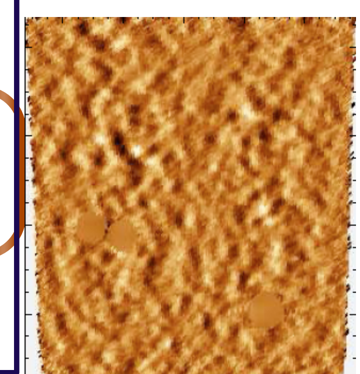


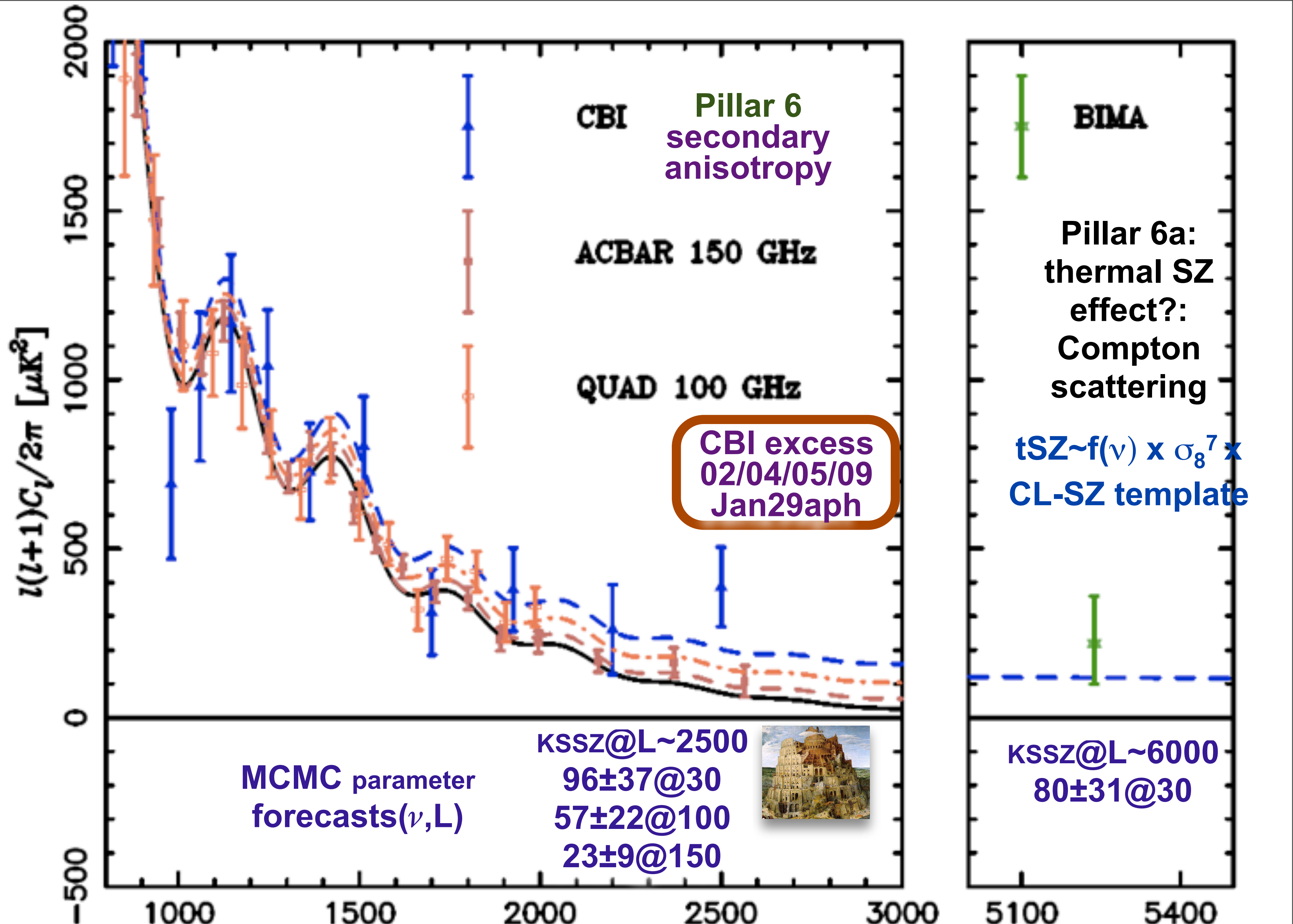


$$C_\ell^{lens} = C_\ell^{no-lens} + q_{lens} \Delta C_\ell^{lens}$$

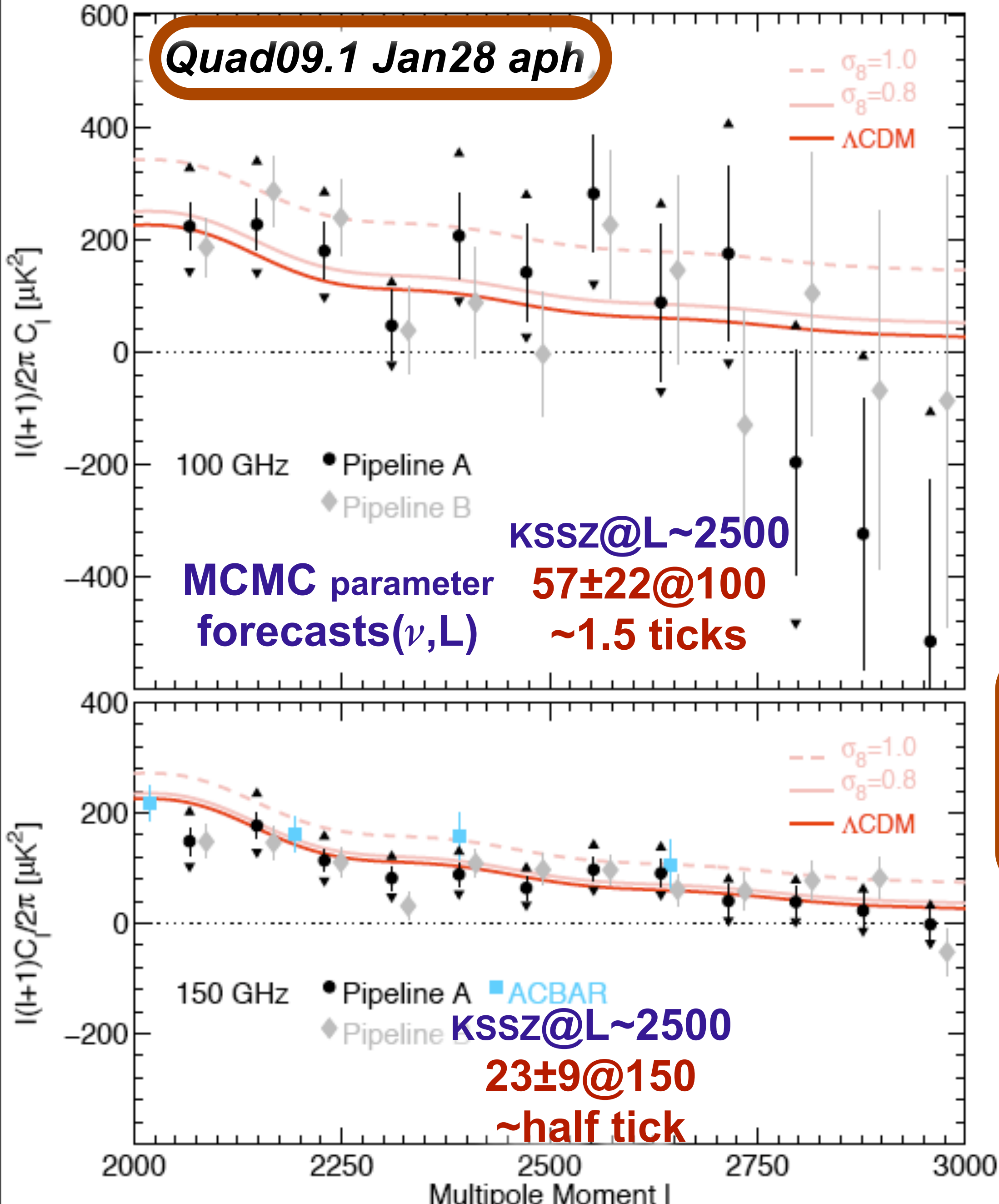
$$\Delta \ln \mathcal{E} = \ln[P(lens|data, theory)/P(no-lens|data, theory)]$$

		Bayesian evidence
wmap5	$q_{lens} = 1.34^{+0.27(+1.51)}_{-0.26(-0.85)}$	$\Delta \ln \mathcal{E} = 2.04$
wmap5+ acbar	$q_{lens} = 1.23^{+0.21(+0.83)}_{-0.23(-0.76)}$	$\Delta \ln \mathcal{E} = 2.89$
CMBall	$q_{lens} = 1.21^{+0.24(+0.82)}_{-0.24(-0.76)}$	$\Delta \ln \mathcal{E} = 2.63$





09Jan29 aph SZA@L~4066 60+65-55@30 ⇒ 34±60 cf. 92±35@30 kSSZ@L~4000



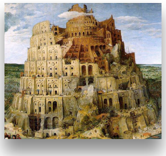
Pillar 6
secondary anisotropy

CBI excess 02/04/05/09.1

Pillar 6a: thermal SZ effect?: Compton scattering

tSZ~f(ν) x σ_8^7 x CL-SZ template

Conclude: QuAD is consistent with the SZ-frequency-scaled CBI excess



ACT@5170m

why Atacama? driest desert in the world. thus: cbi, toco, apex, asti, act, alma, quiet, clover

CBI2@5040m

CBI pol to Apr'05 @Chile

CBI2

QUaD @SP

Quiet1 @Chile

Quiet2 1000 HEMTs

Boom03@LDB

Bicep @SP

Bicep2

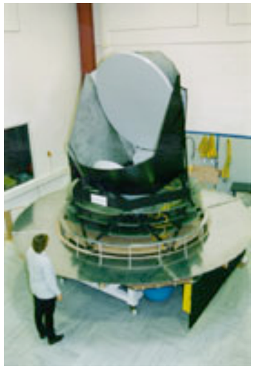
Keck/Spud

WMAP @L2 to 2009-2013?

Planck09.3

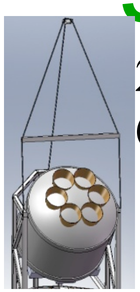
(52 bolometers) + HEMTs @L2

9 frequencies



EBEX @LDB

Spider 2312 bolos @LDB



DASI @SP

CAPMAP

Herschel

BLAST

CHIP

2004 2005 2006 2007 2008 2009 2011

LHC

Bpol @L2

Acbar to Jan'06, 08f @SP

SPT 1000 bolos @SPole

BLASTpol

Clover @Chile

SZA @Cal

ACT 3000 bolos 3 freqs @Chile

Polarbear 300 bolos @Cal/Chile

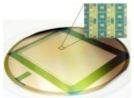
SPTpol

AMI

GBT

APEX ~400 bolos @Chile

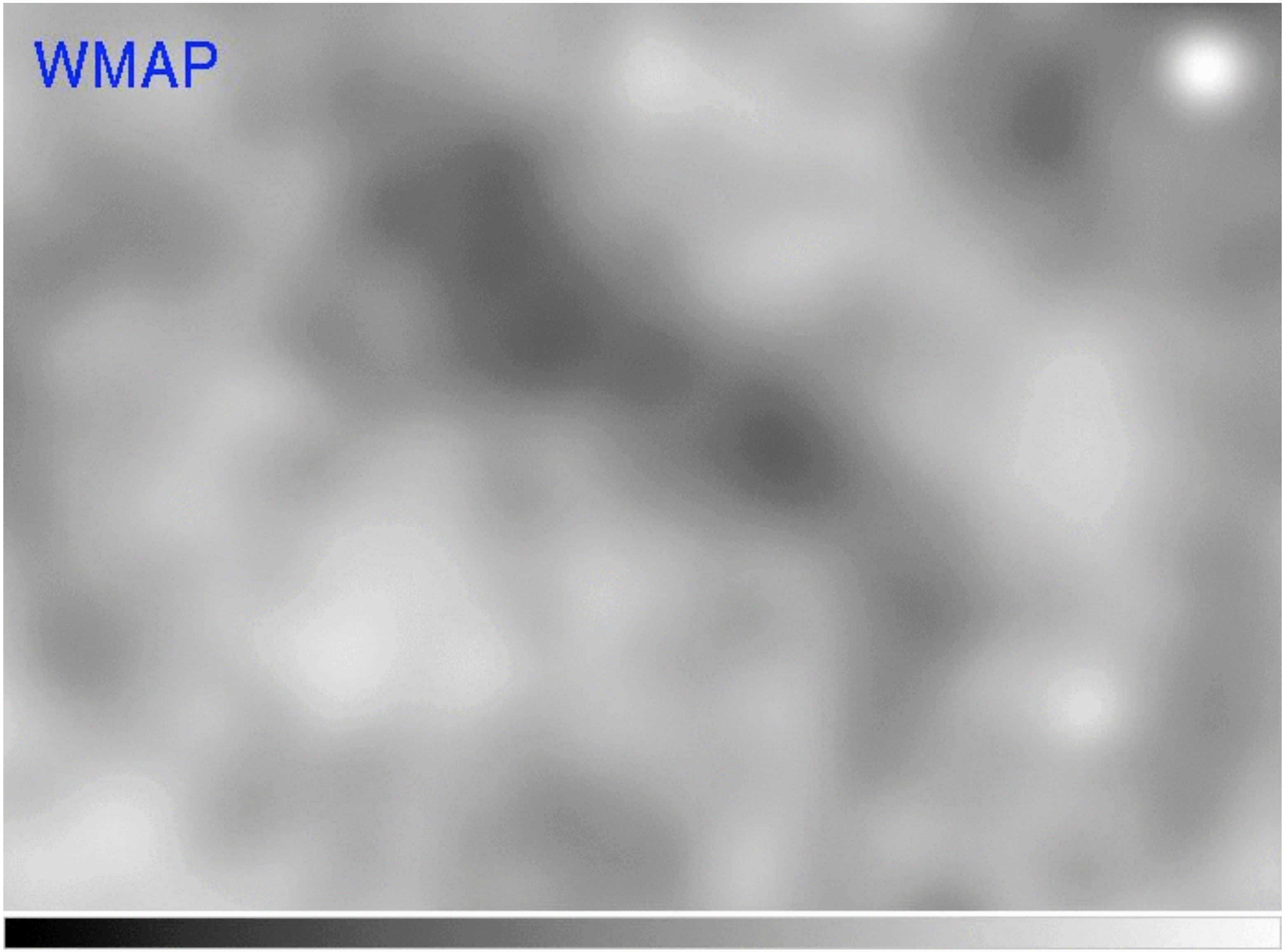
SCUBA2 12000 bolos JCMT @Hawaii



ALMA @Chile

LMT@Mexico

WMAP⇒BOOM⇒ACBAR⇒ACT
the high resolution CMB frontier



Toby Marriage, ACTor

Peebles, Page, Partridge, *Finding the Big Bang*, Feb09 CUP

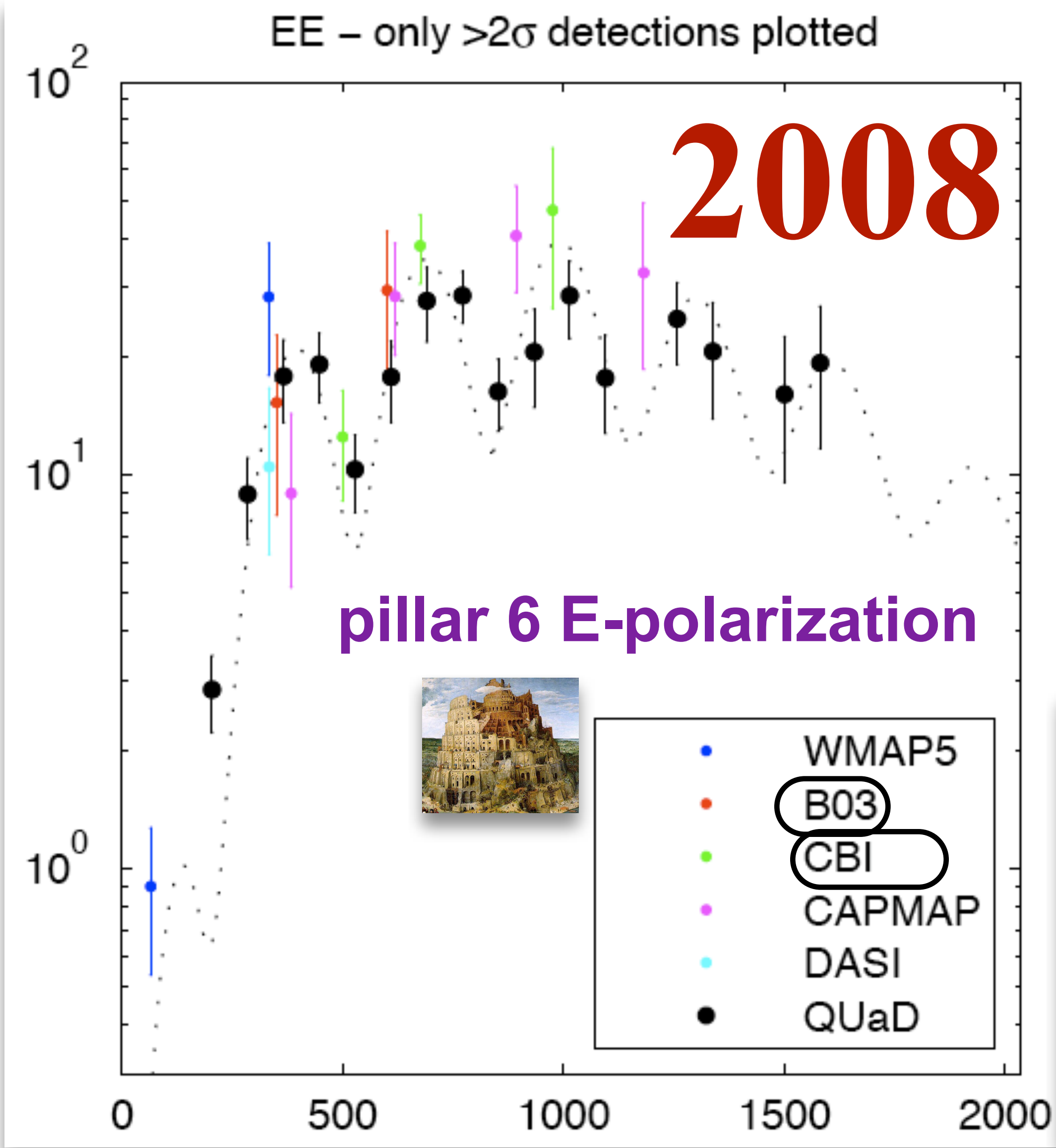
Rees 1968: CMB should be polarized; detection 2002 DASI

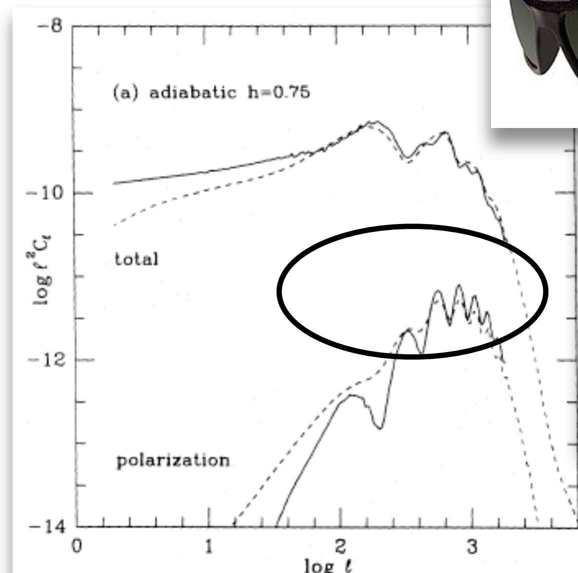
Kaiser83, pol via line-of-sight integration
BE84: pol via Boltzmann transport, ~7% target, effect on shear viscosity, damping tail, "E" mode
BE87: low to high L full CLpol, maps
Crittenden & Turok 96: TE correlation **DASI02,WMAP03**
Kaiser95, Stebbins96: rotate lensing E to B, a null test
Kamionkowski, Kosowsky & Stebbins97 & Seljak & Zaldarriaga97: apply to CMB E/B modes. emphasize as gravity wave discriminator
Zaldarriaga & Seljak98 lensing distorts E into B

First E detection DASI 2002; CBI04/05, Boom05, WMAP06, Capmap08, QuAD08; BICEP09?

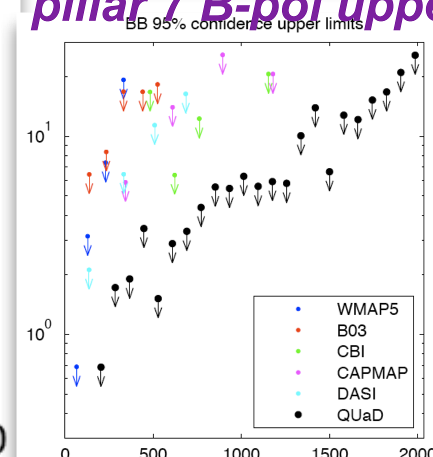
emergence of CMB polarization *power*

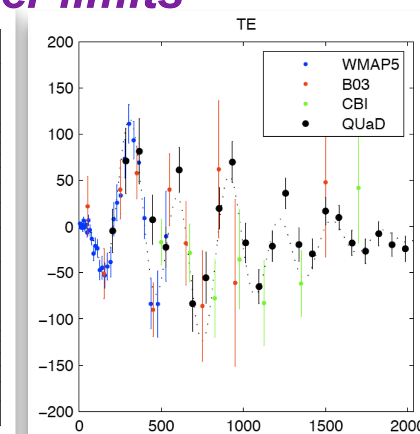
DASI02,04 CBI04 Boom05 CBI05 WMAP3,5 QUaD07,08





pillar 7 B-pol upper limits





What is the Universe made of?

NOW: baryons + (cold-ish) dark matter + dark energy/inflaton + tiny curvature energy** (+light neutrinos+photons). ??a bit of strings/textures/PBHs??* ***web of galaxies/clusters

THEN: coherent inflaton /**"vacuum" energy** plus **zero-point fluctuations** in all fields (≈*Gaussian RF*) & then preheat via mode coupling to incoherent cascade to thermal equilibrium aka **quark-gluon plasma**

& how was it, is it & will it be distributed?

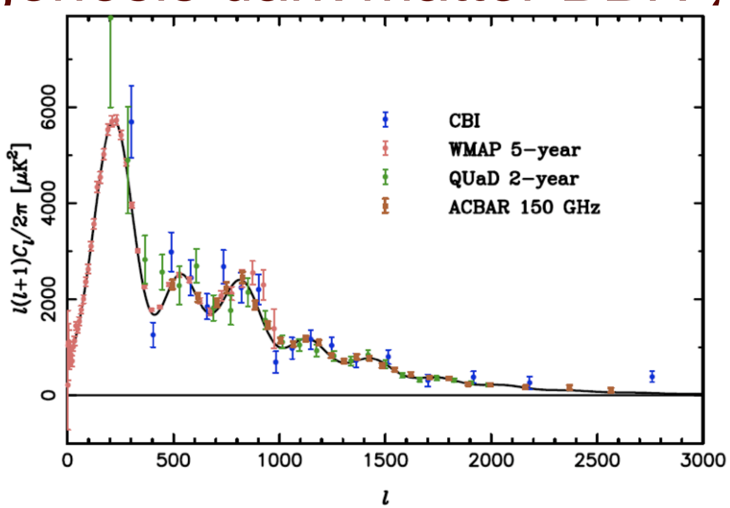
very early U early to middle to now U **very late U**

string theory/landscape/higher dimensions

inflation cyclic baryogenesis dark matter BBN γdec **dark energy**

$V_{eff}(\psi_{inf})$?

$K_{eff}(\psi_{inf})$?



$V_{eff}(\psi_{inf})$?

$K_{eff}(\psi_{inf})$?

cosmic mysteries

n_b/n_γ ρ_{dm}/ρ_b z_{eq}/z_{rec} ρ_{curv} ρ_{de}/ρ_{dm} $\rho_{de} \sim H^2 M^2_{Planck}$ $\rho_{m\nu}/\rho_{stars}$

$\Rightarrow$ exquisite & increasingly precise determination of cosmic parameters

dark matter abundance Ω_m=0.268 +.012 -.012

	January 2000	January 2002	June 2002	January 2003	March 2003
$\Omega_{cdm}h^2$	$0.198^{+0.088}_{-0.080}$	$0.130^{+0.031}_{-0.028}$	$0.124^{+0.026}_{-0.025}$	$0.125^{+0.021}_{-0.022}$	$0.111^{+0.010}_{-0.010}$

CMB-only history (weak-h prior). LSS-then drove to near current

$\Omega_{dm}h^2$ 0.1145 +-0.0023 CMBall+WL+LSS+SN+Lya

$\Omega_b h^2$ 0.0233 +- 0.0005 ordinary matter abundance (baryons)

$\Rightarrow \rho_{dm}/\rho_b$ =5.1

Ω_Λ	$0.34^{+0.28}_{-0.24}$	$0.52^{+0.17}_{-0.20}$	$0.53^{+0.17}_{-0.19}$	$0.57^{+0.14}_{-0.19}$	$0.73^{+0.06}_{-0.10}$

CMB-only history (weak-h prior). LSS-then drove to near current value

dark energy abundance Ω_Λ=0.736 +.012 -.012

& H_0 = 72 +-1 CMBall+WL+LSS+SN+Lya

$\Rightarrow \rho_m/\rho_{de}$ =.30

ε=-dlnH/dlna=1+q: now =3/2[Ω_{m0} +(1+w)(1-Ω_{m0})] ~0.40?, to 0?

Standard & Parameters of Cosmic Structure Formation

$\Omega_b h^2$ $\Omega_{dm} h^2$ Ω_Λ Ω_k τ_c

$\ln A_s$ n_s $r = A_t / A_s$ $dn_s / d\ln k$ n_t

$1+w_0, w_a$ $\theta \sim \ell_s^{-1}$ $\sim \ln \sigma_8^2$

+ subdominant isocurvature/ cosmic string ***& fgnds, tSZ,kSZ, ...***

+ primordial non-Gaussianity

$\Phi(x) = \Phi_G(x) + f_{NL} (\Phi_G^2(x) - \langle \Phi_G^2 \rangle)$

local smooth

$\Phi(x) = \Phi_G(x) + F_{NL}(\chi_b) - \langle F_{NL} \rangle$

resonant preheating

new parameters: trajectory probabilities for early-inflatons & late-inflatons

(partially) blind cf. informed "theory" priors

CBI pol to Apr'05 @Chile

QUaD @SP

Quiet1 @Chile

Quiet2 1000 HEMTs

Boom03@LDB

Bicep @SP

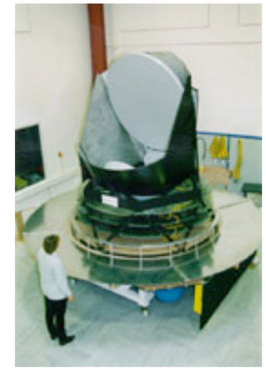
Bicep2

Keck/Spud

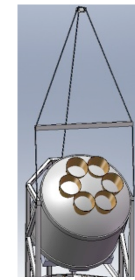
WMAP @L2 to 2009-2013?

Planck09.3

(52 bolometers)
+ HEMTs @L2
9 frequencies



EBEX @LDB



Spider
2312 bolos
@LDB

DASI @SP

CAPMAP

CHIP

2004 2005 2006 2007 2008 2009 2011

LHC

Bpol @L2

BLASTpol

Clover @Chile

Polarbear
300 bolos
@Cal/Chile

SPTpol

INFLATION THEN

PROBES NOW

"standard inflation space": n_s $dn_s/d\ln k$ r @k-pivots

$n_s(k_p)$=.962 +-.013 (+-.005 Planck1) .959 +- .011 all data

$r=P_t/P_s(k_p')$ < 0.40_{cmb} 95% CL (+-.03 P1, +- .01 Spider+P2.5)

$dn_s/d\ln k$ (k_p) =-.016 +- .019 (+-.005 Planck1)

(partially) blind trajectories e.g., $n_s(k)$ and $r(k_p)$, *are better*

local quadratic non-G constraint: $-9 < f_{NL} < 111 \Rightarrow -4 < f_{NL} < 80$ WMAP5 (± 5-10 Planck1yr)

CBI10: add a cosmic string template⇒n_s<1 @2σ & string tension limit $G\mu < 2.8 \times 10^{-7}$

INFLATION THEN

WHAT IS PREDICTED?

Smoothly broken scale invariance by nearly uniform braking (standard of 80s/90s/00s) $r \sim 0.03 - 0.5$

or highly variable braking r tiny

(stringy cosmology) $r < 10^{-10}$

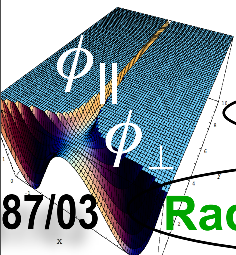
Old view: **Theory prior = delta function of THE correct one and only theory**

New: Theory prior = probability distribution of **late-flows** on an **energy LANDSCAPE**

6/7 tiny extra dimensions

1980 — R^2-inflation · Old Inflation · **Chaotic inflation**

New Inflation



Double Inflation · Power-law inflation · SUGRA inflation

87/03 **Radical BSI inflation** · **variable M_P inflation** · Extended inflation

1990

Natural pNGB inflation · Hybrid inflation

Assisted inflation

SUSY F-term inflation · SUSY D-term inflation

Brane inflation

2000

SUSY P-term inflation · Super-natural Inflation · K-flation

2003 KKLT

N-flation

ekpyrotic/cyclic

D3,D7 brane inflation · DBI inflation

moving brane separations

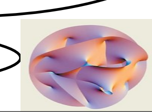
Warped Brane inflation

Tachyon inflation

Racetrack inflation

moduli fields

monodromy · **Roulette inflation Kahler moduli/axion**



very early U | early to middle to now U | **very late U**

inflation | *string theory/landscape/higher dimensions* | **dark energy**

$V_{eff}(\psi_{inf})$? partial shape reconstruction | reconstruct gradient $V_{eff}(\psi_{inf})$?

$K_{eff}(\psi_{inf})$? | $K_{eff}(\psi_{inf})$?

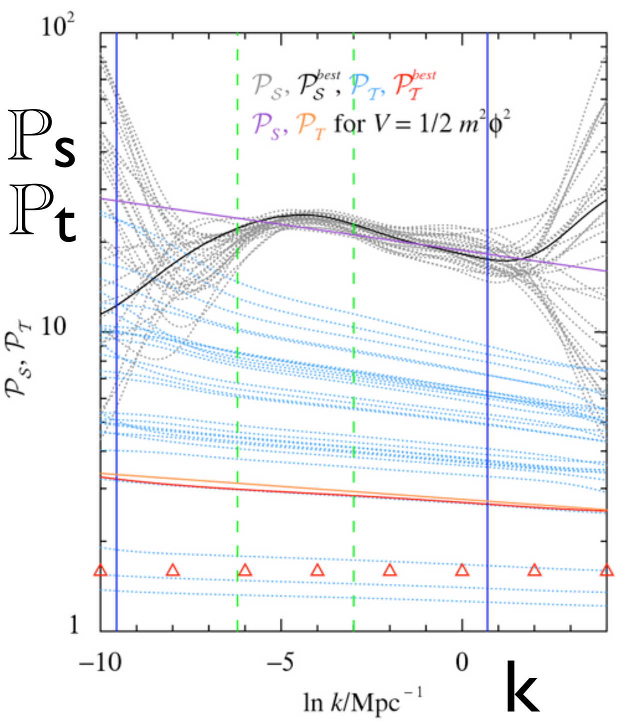
trajectory probability

$-d\ln\rho_{tot}/d\ln a\ /2$

$= \varepsilon(k) = 1+q,\ k \sim Ha$

$\Rightarrow \mathbb{P}_s, \mathbb{P}_t$

$\mathbb{V}_{eff}(k)$, $\psi_{inf}(k)$



trajectory probability

$-d\ln\rho_\phi/d\ln a\ /2$

$= \varepsilon_\phi(a) = (1+w)2/3$

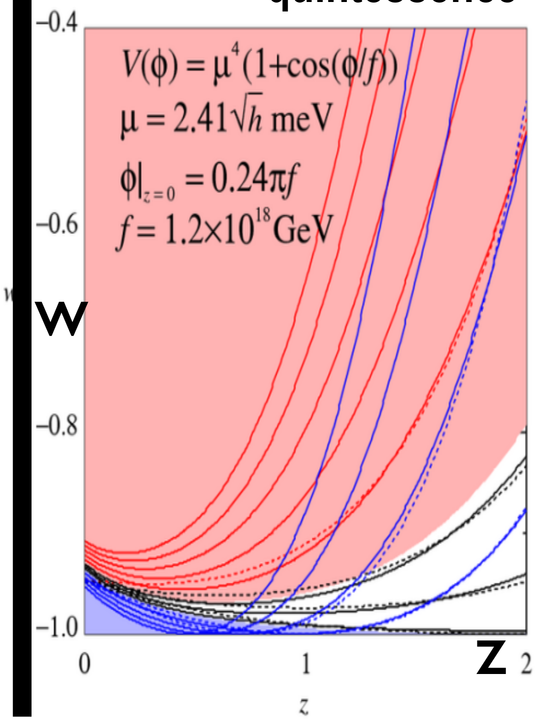
$\Rightarrow$

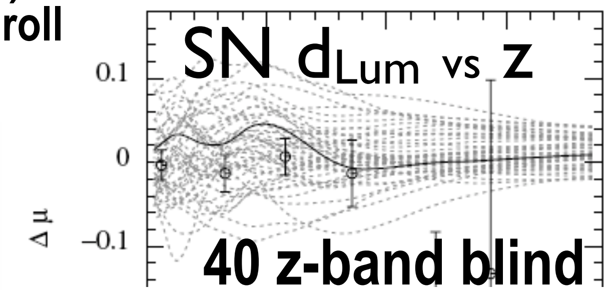
$\varepsilon_s = (d\ln V/d\psi)^2/4$

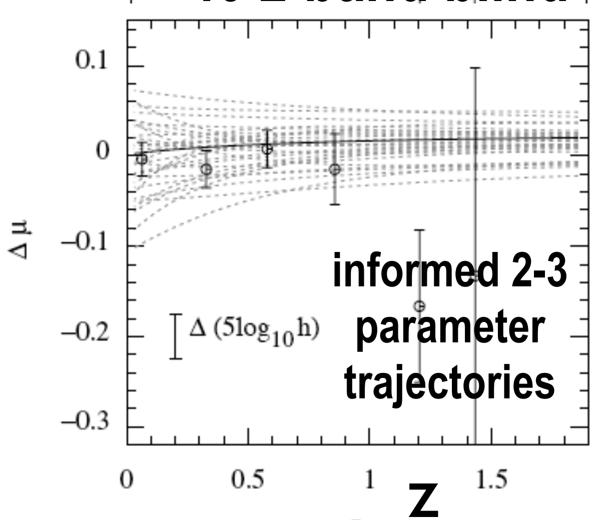
@pivot a_{eq} **yes**

$d^2\ln V/d\psi^2\ /4$ **no**

slow-to-moderate roll quintessence







INFLATION NOW

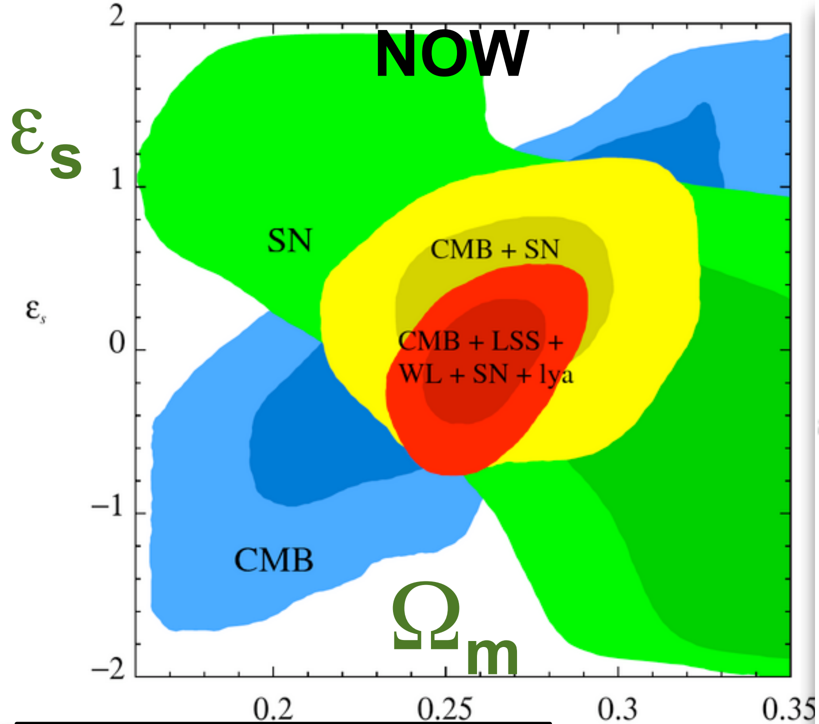
PROBES NOW & THEN

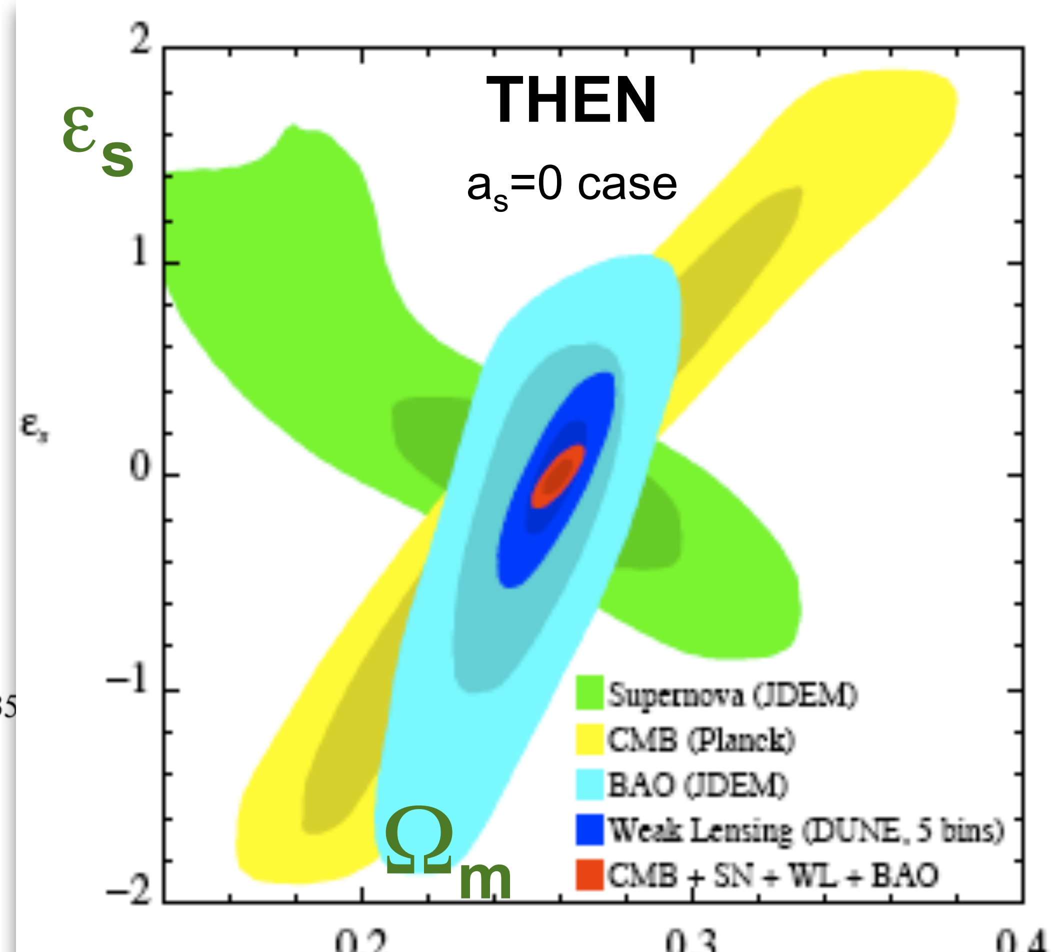
Beyond Einstein panel: LISA+JDEM

Forecast: JDEM-SN (2500 hi-z + 500 low-z) + DUNE-WL (50% sky, gals @z = 0.1-1.1, 35/min^2) + Planck1yr

now ESA /Eucid

ESA (+NASA/CSA)





$1+\mathbf{w_0} = -0.0 \pm 0.06$

$\varepsilon_s = (d\ln V/d\psi)^2/4$ @pivot a_{eq}

$= -.03 + .26 - .30 \;\; 2$

$\zeta_s = \pm_{1.001} d^2 \ln V/d\psi^2 /4 \quad = 0.1 \pm 0.7$

$\varepsilon_s = 0.00^{+0.07}_{-0.06}$ Ω_m $\zeta_s = 0.1 \pm 0.7$

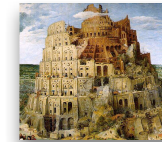
cannot reconstruct the quintessence potential, just the slope ε_s & ~hubble drag

INFLATION
THEN

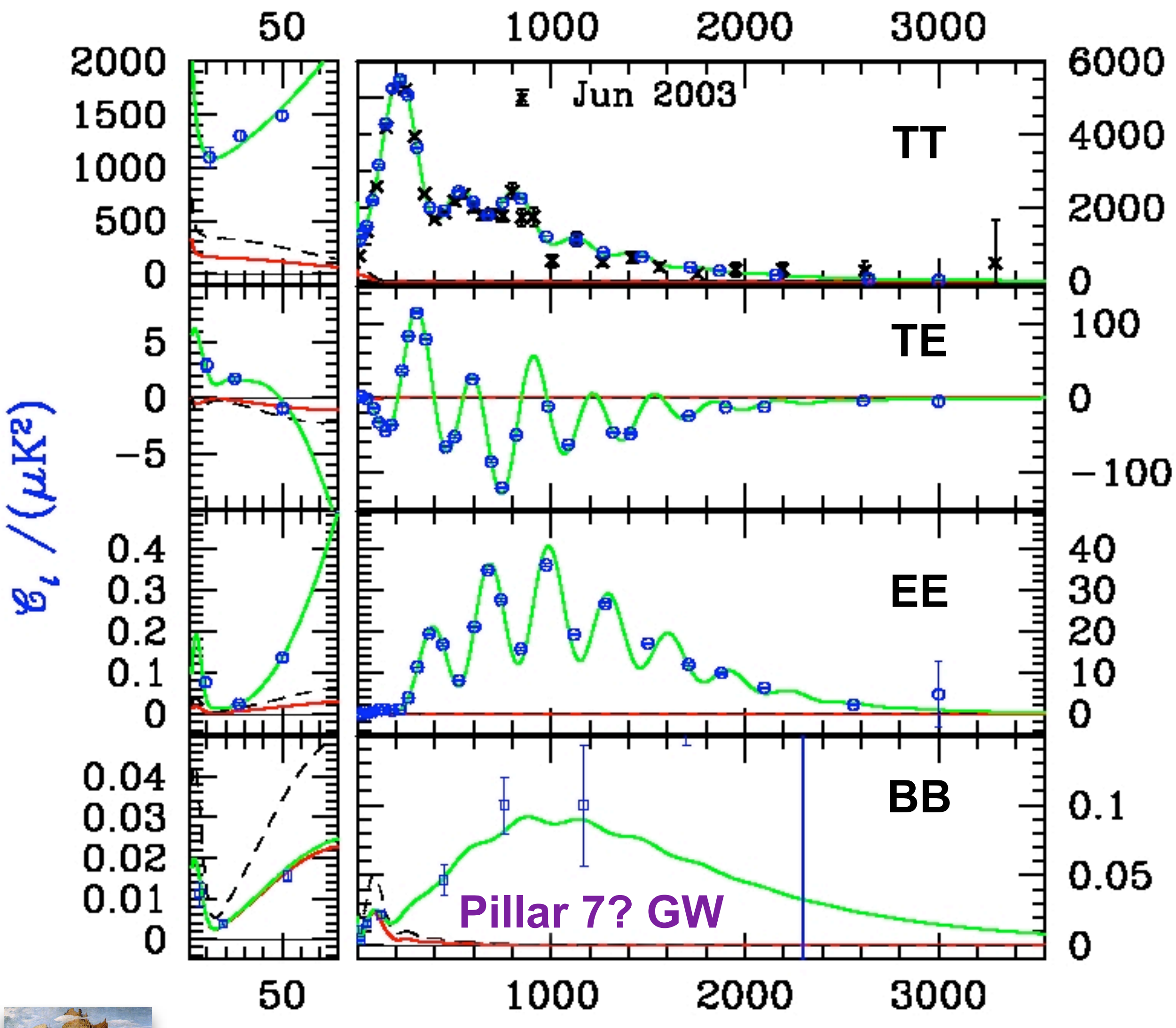
PROBES
THEN

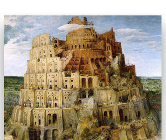
PRIMARY END @ 2012?

CMB ~2009+ Planck1+WMAP8+SPT/ACT/Quiet+Bicep/QuAD/Quiet +Spider+Clover



Pillar 7? Gravity Waves



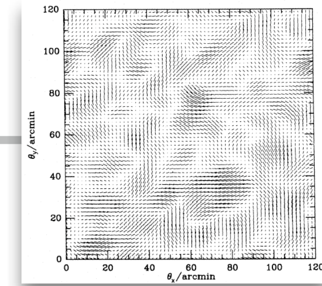


+ Pillar 4: primordial non-Gaussianity -9< f_{NL} <111 (+- 5-10 Planck1)

SPIDER Tensor Signal

Pillar 7

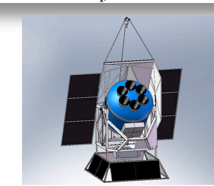
Gravity Waves from **Inflation**



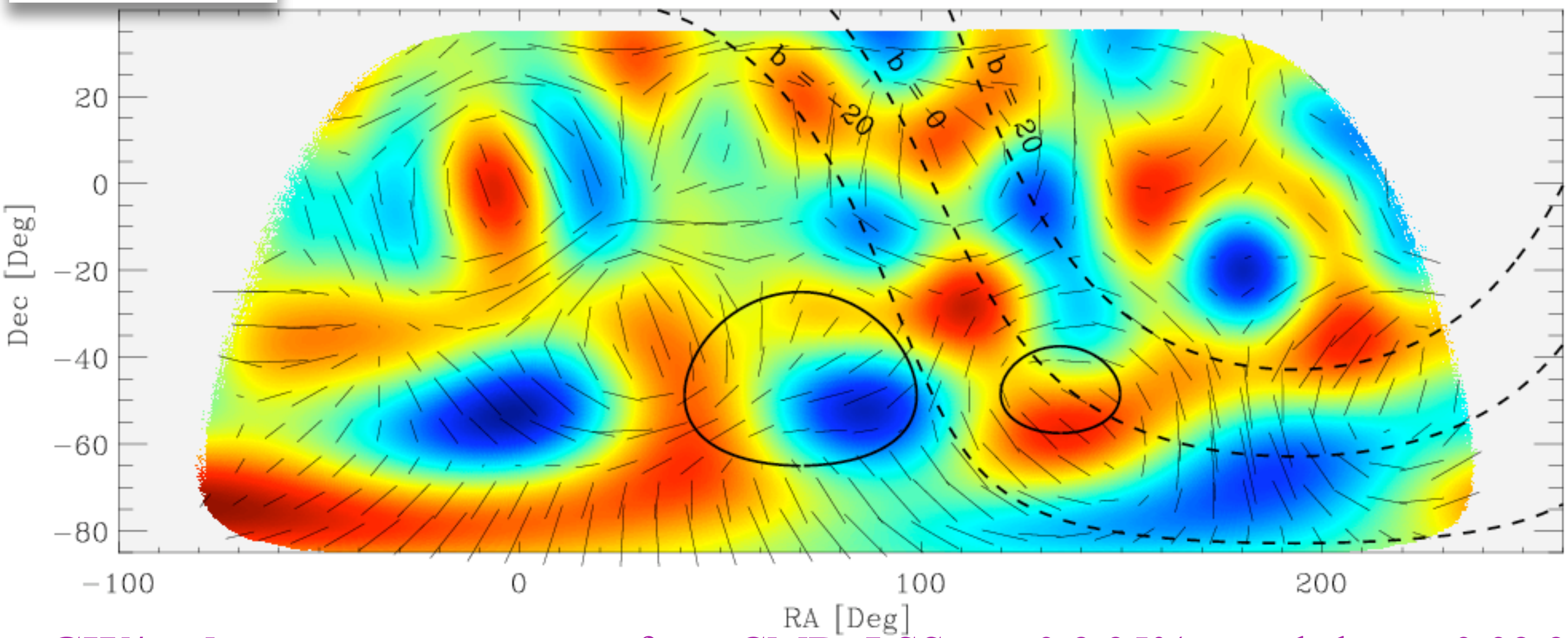
- Simulation of large scale polarization signal

http://www.astro.caltech.edu/~lgg/spider_front.htm

$$\frac{A_T}{A_S} = 0.1$$



Tensor



GW/scalar curvature: current from CMB+LSS: r < **0.3** 95%; good shot at **0.02** 95% CL with **BB polarization** (+- **.02 PL2.5+Spider**), **.01 target; Bpol .001** BUT foregrounds/systematics? But **r(k), low Energy inflation**

SPIDER Tensor Signal

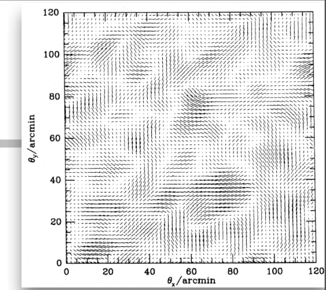
Pillar 7

Gravity Waves from **Inflation**

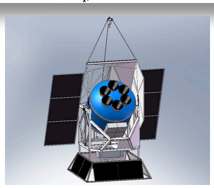
- **Simulation of large scale polarization signal**

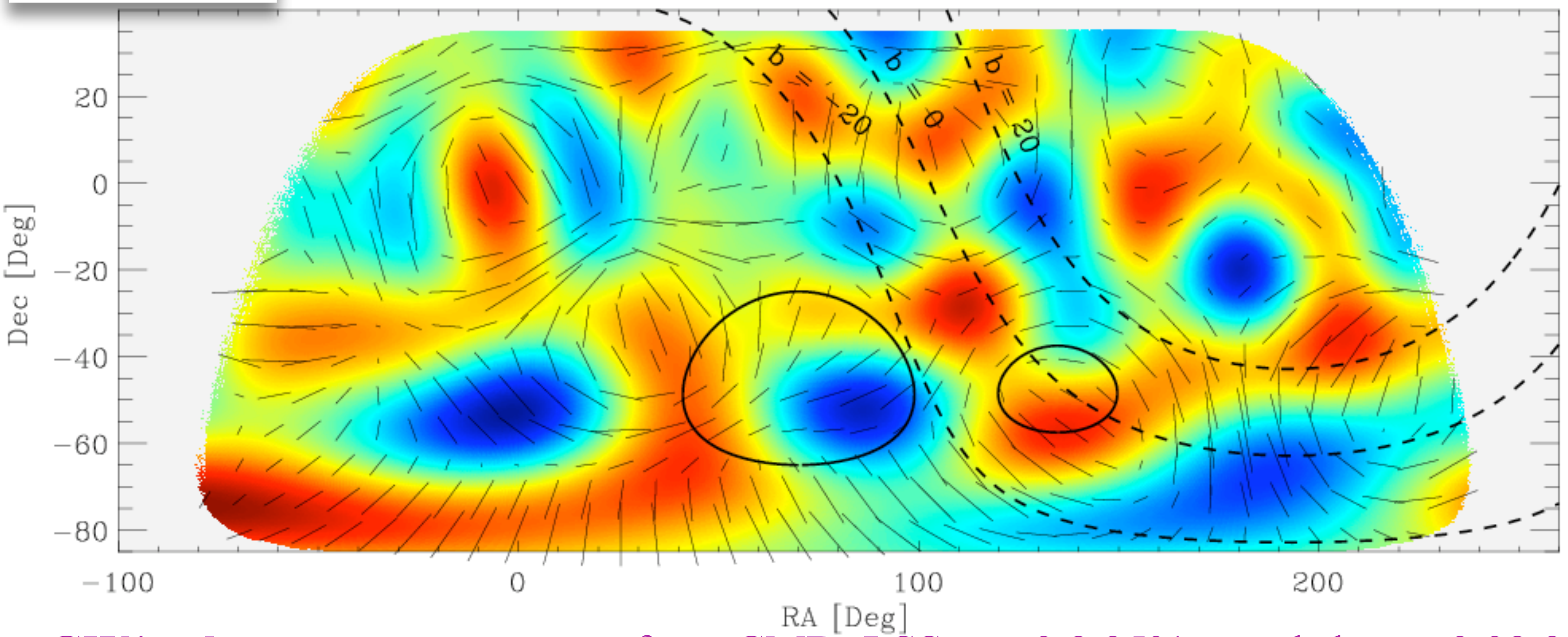
http://www.astro.caltech.edu/~lgg/spider_front.htm

$$\frac{A_T}{A_S} = 0.1$$



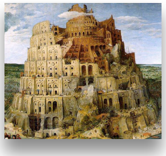
No Tensor



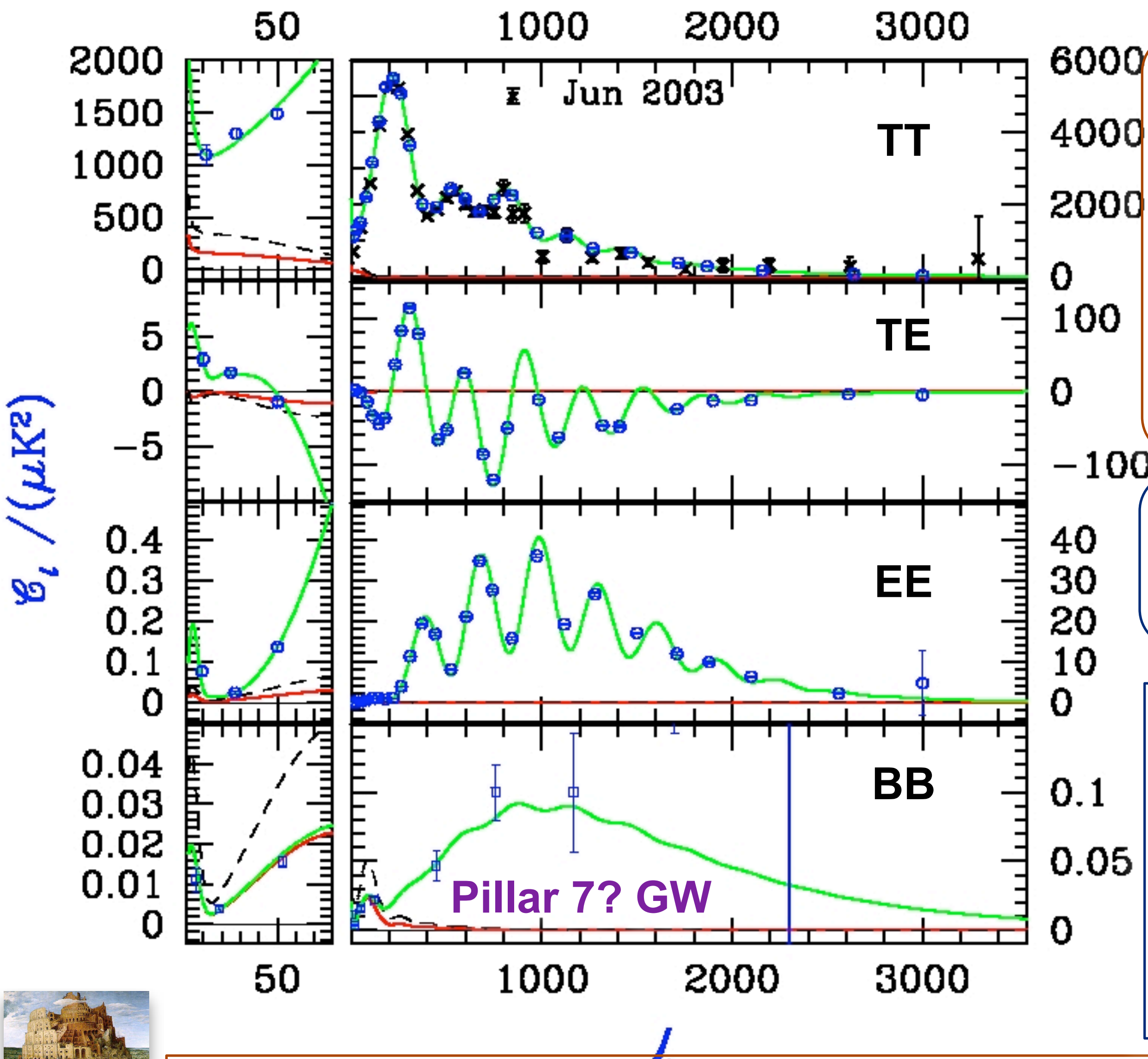


GW/scalar curvature: current from CMB+LSS: r < **0.3** 95%; good shot at **0.02** 95% CL with **BB polarization** (**+- .02 PL2.5+Spider), .01 target; Bpol .001** BUT foregrounds/systematics? But **r(k), low Energy inflation**

PRIMARY END @ 2012?



CMB ~2009+ Planck1+WMAP8+SPT/ACT/Quiet+Bicep/QuAD/Quiet +Spider+Clover



Pillar 7? Gravity Waves

An ensemble of trajectories arises in many-moduli string models, whether braney or holey. **Roulette inflation:** *complex hole sizes in 6D* TINY **$r<10^{-10}$** *& n_s from data-selected braking!*

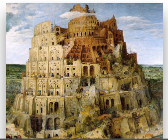
('theorem': $\Delta\psi< 1$ -> **$r<.007$**)

nearly uniform acceleration

(power law, exp, PNGB, ..potentials)

$r\sim.03-.3$! is $\Delta\psi\sim10$ deadly?

*Even with low energy inflation, the prospects are good with **Spider** plus **Planck** to either detect the GW-induced B-polarization or set a strong blind upper limit **r<0.02** indicating stringy or other exotic models. Both experiments have strong Cdn roles. **Bpol 2020?, to r~0.002***



+ Pillar 4: primordial non-Gaussianity **$-4< f_{NL}<80$ (+- 5-10 Planck1)**

end1

The Past, Present & Future of Random Fields in Cosmology

What is the Universe made of & how was it, is it & will it be distributed?

NOW: baryons/leptons + (cold-ish) dark matter + dark energy/inflaton + tiny curvature energy (+photons+light neutrinos + *gravity waves*). *??a bit of strings/textures/PBHs??* ***web of galaxies/clusters***

THEN: coherent inflaton /**"vacuum" energy** + **zero-point fluctuations** in all fields (*Gaussian RF*) & then preheat via mode coupling to incoherent cascade to thermal equilibrium soup

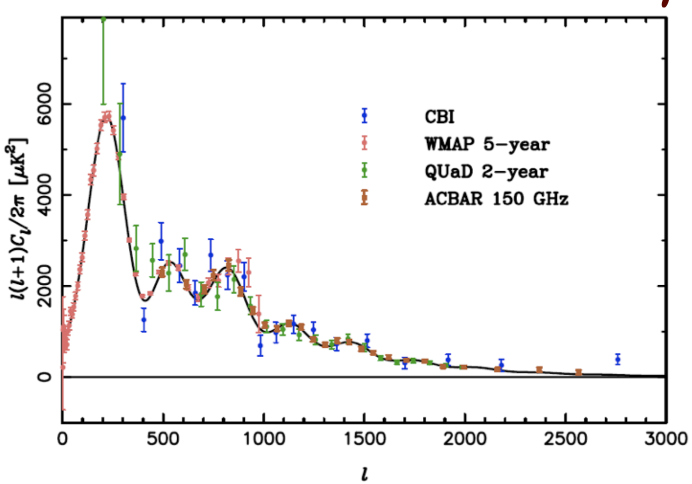
very early U early to middle to now U **very late U**

string theory/landscape/higher dimensions

inflation cyclic baryogenesis dark matter BBN γdec **dark energy**

$V_{eff}(\psi_{inf})$?

$K_{eff}(\psi_{inf})$?

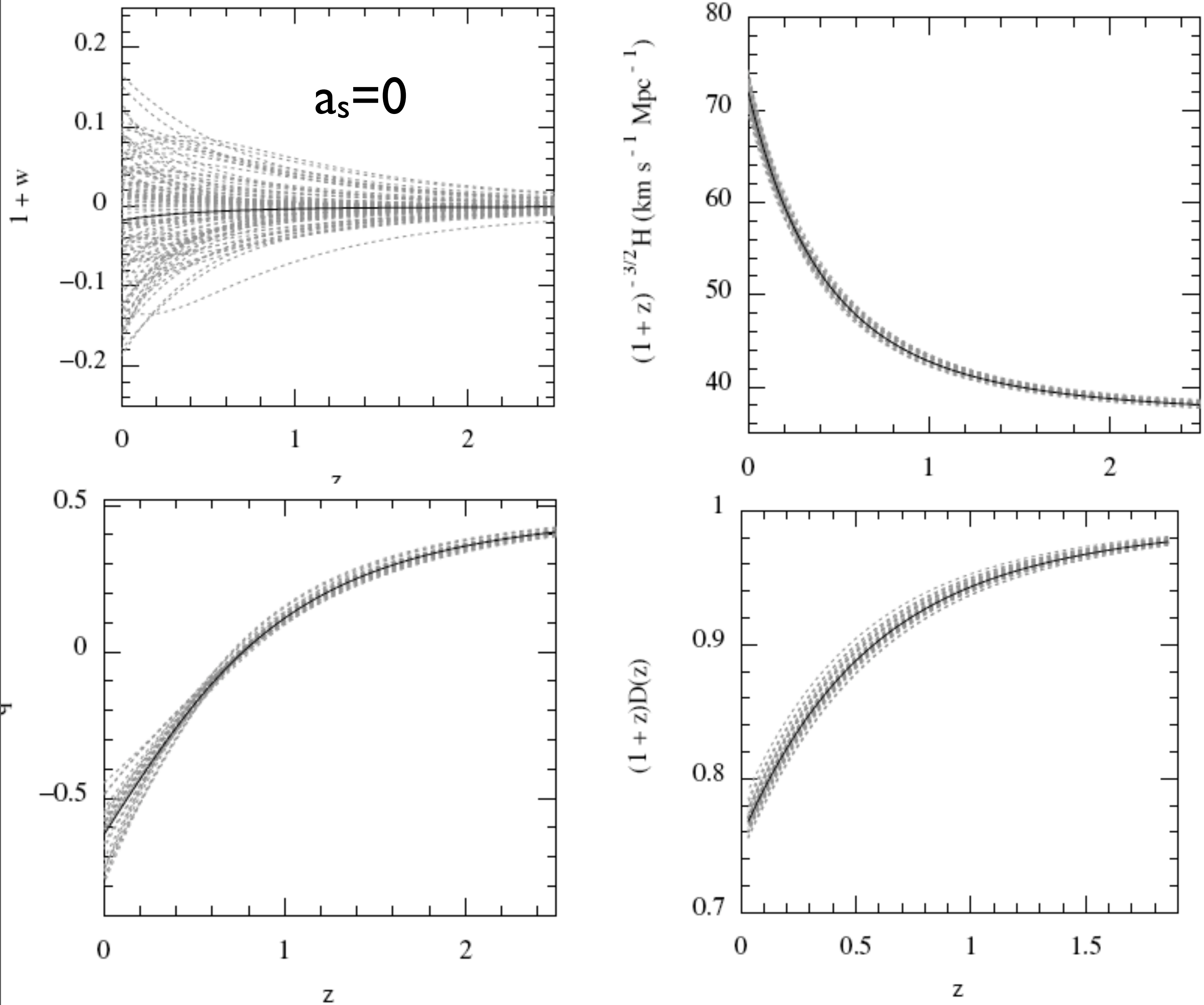


$V_{eff}(\psi_{inf})$?

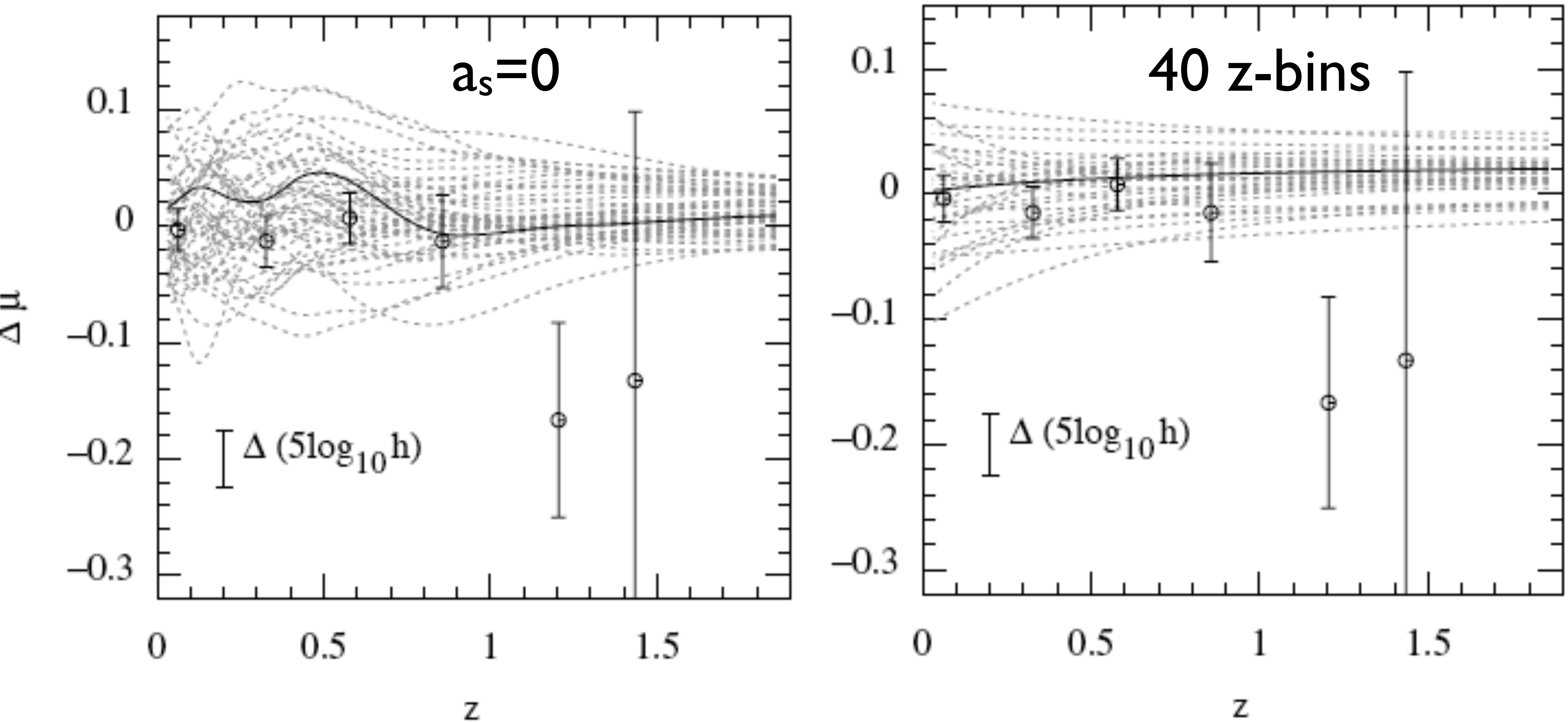
$K_{eff}(\psi_{inf})$?

cosmic mysteries

n_b/n_γ ρ_{dm}/ρ_b z_{eq}/z_{rec} ρ_{curv} ρ_{de}/ρ_{dm} $\rho_{de} \sim H^2 M^2_{Planck}$ $\rho_{m\nu}/\rho_{stars}$



a_s=0
1 + w
0.2
0.1
0
−0.1
−0.2
0
1
2
z
(1 + z)^-3/2 H (km s^-1 Mpc^-1)
80
70
60
50
40
0
1
2
0.5
0
−0.5
0
1
2
z
(1 + z)D(z)
1
0.9
0.8
0.7
0
0.5
1
1.5
z


as=0
40 z-bins
Δ μ
Δ (5log10h)
z
0.1
0
−0.1
−0.2
−0.3
0
0.5
1
1.5

Standard & New Parameters of Cosmic Structure Formation

$\Omega_b h^2$ $\Omega_{dm} h^2$ Ω_Λ Ω_k τ_c

$\ln A_s$ n_s $r = A_t/A_s$ $dn_s/d\ln k$ n_t

$1+w_0, w_a$

$\theta \sim \ell_s^{-1}$

$\sim \ln \sigma_8^2$

$n_e(a)$

$\varepsilon_\phi = (1+w(a)) \times 3/2 = -d\ln\rho_\phi/d\ln a/2$

$\varepsilon_s f(a/a_{\Lambda eq}; a_s/a_{\Lambda eq}; \zeta_s)$

$\ln P_s(\ln k)$ & $r(k_p)$ & $\ln P_t(\ln k)$

+ subdominant isocurvature/ cosmic string ***& fgnds, tSZ,kSZ, ...***

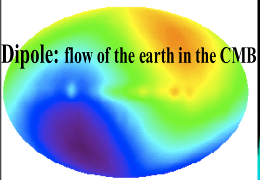
Blind trajectory analysis cf. data, then & now

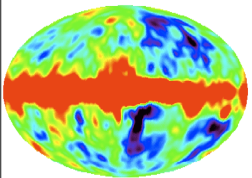
expand ε $(\ln k)/\varepsilon_\phi(\ln a)$ ***in localized mode fns***

*e.g., **Chebyshev/B-spline coefficients*** ε_b

ε_b***-measures: "theory prior"=informed prior?***

$\varepsilon_\phi(\ln k)$, $k \sim Ha$ & $\ln H(k_p)$

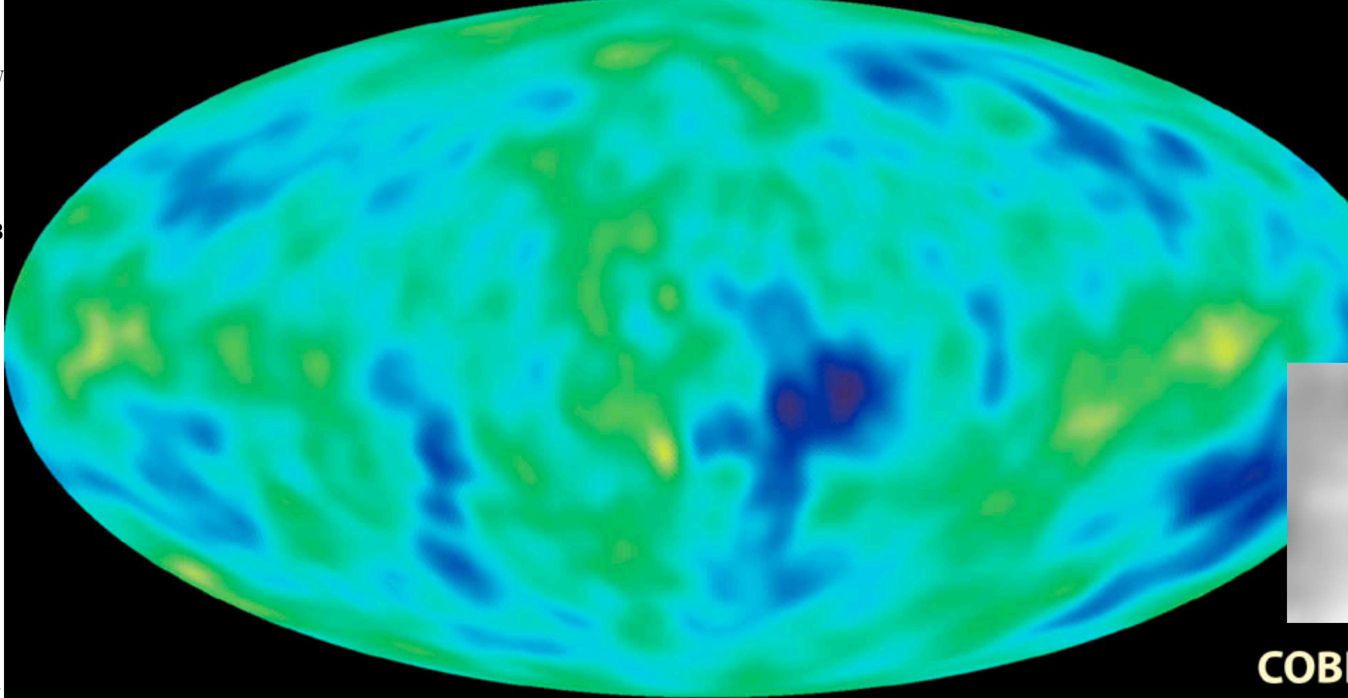


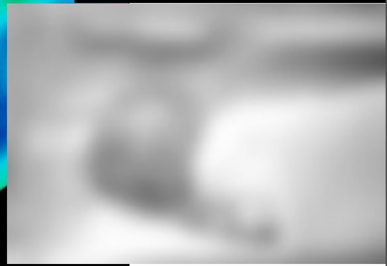


COBE/DMR:
CMB + Galactic @7^0

is this a statistically isotropic Gaussian random field, when account is taken of the Milky Way emissions & extra-galactic sources?

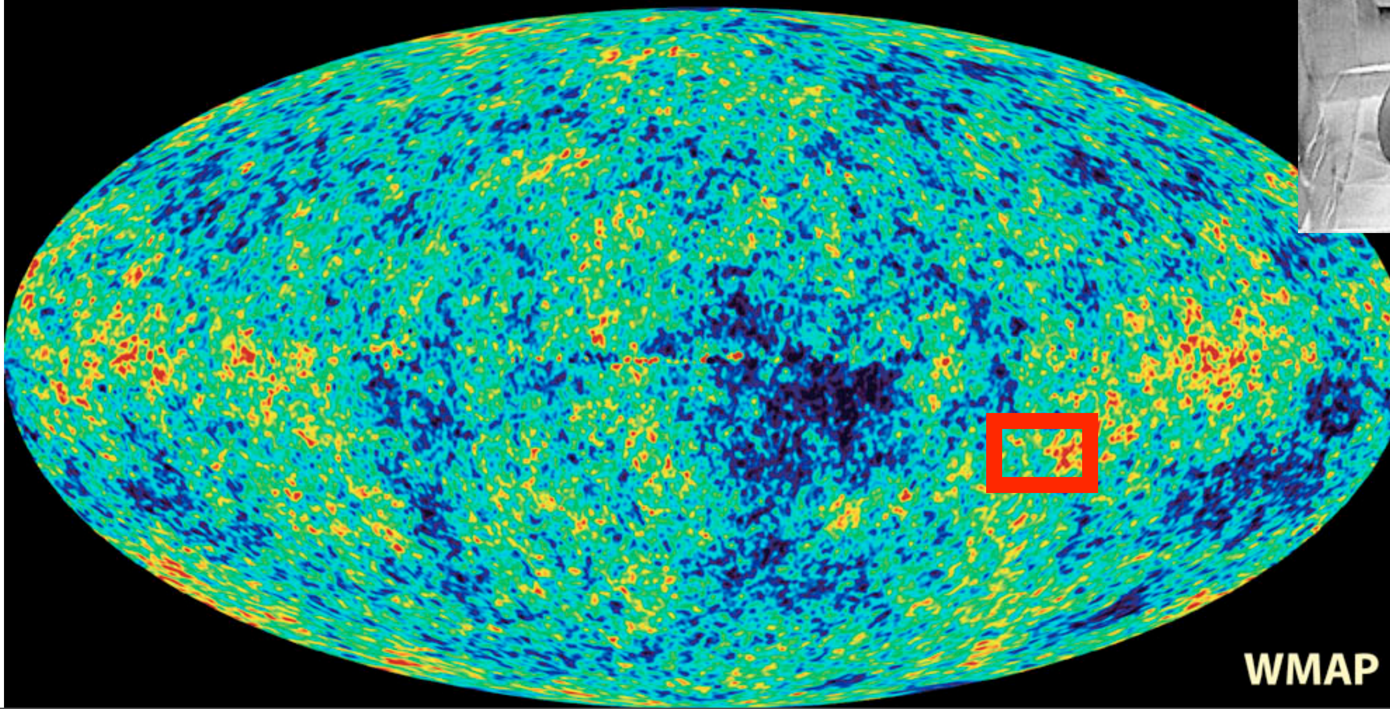
yes! maybe?

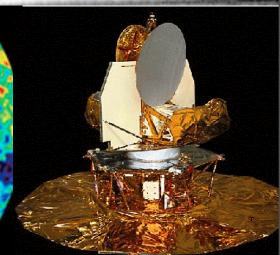




COBE

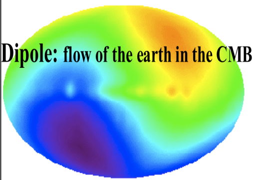
1992/96

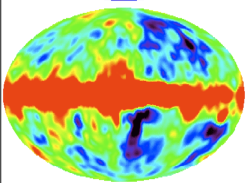




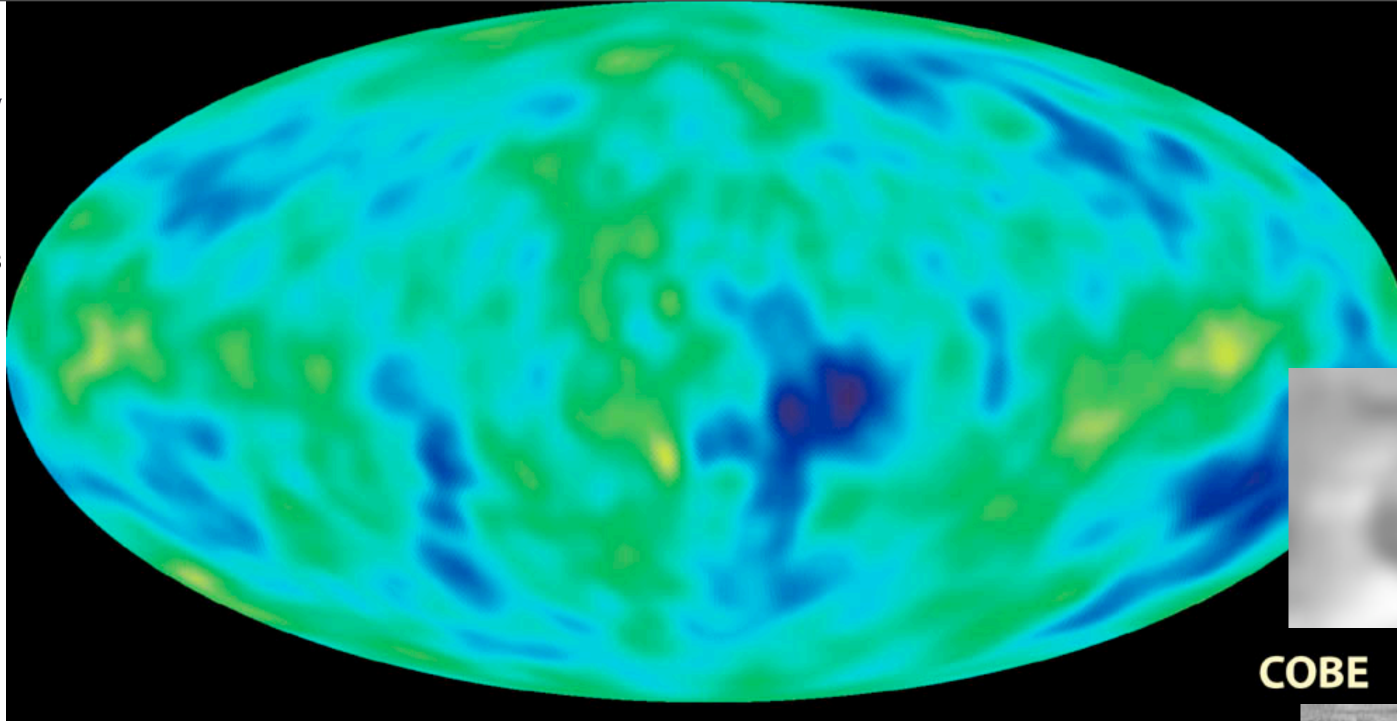
WMAP

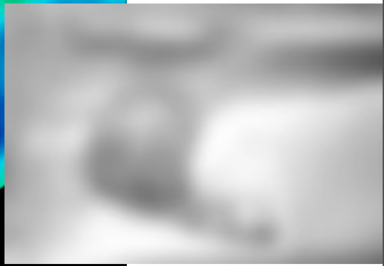
Feb03
Mar06
Mar08





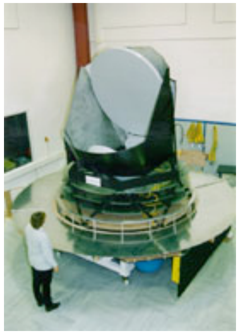
COBE/DMR:
CMB + Galactic @7°

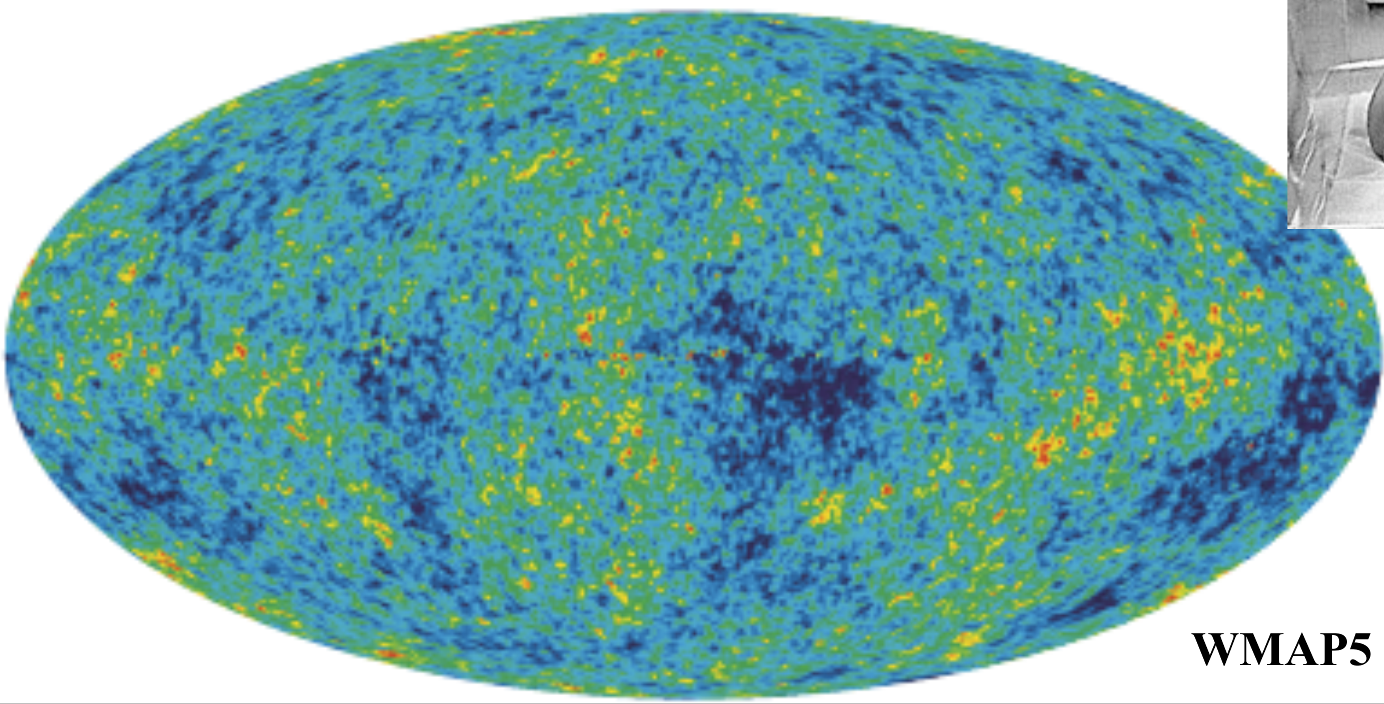




1992/96

Planck satellite April09 launch



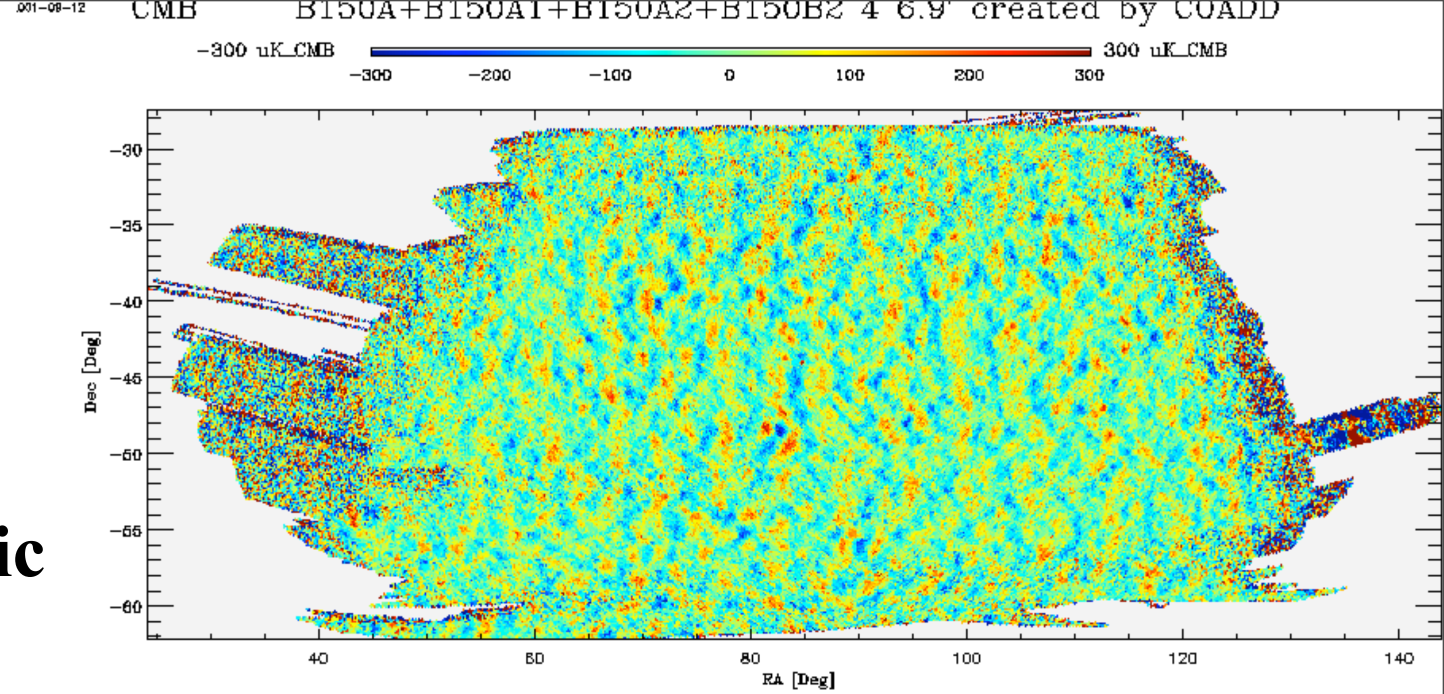


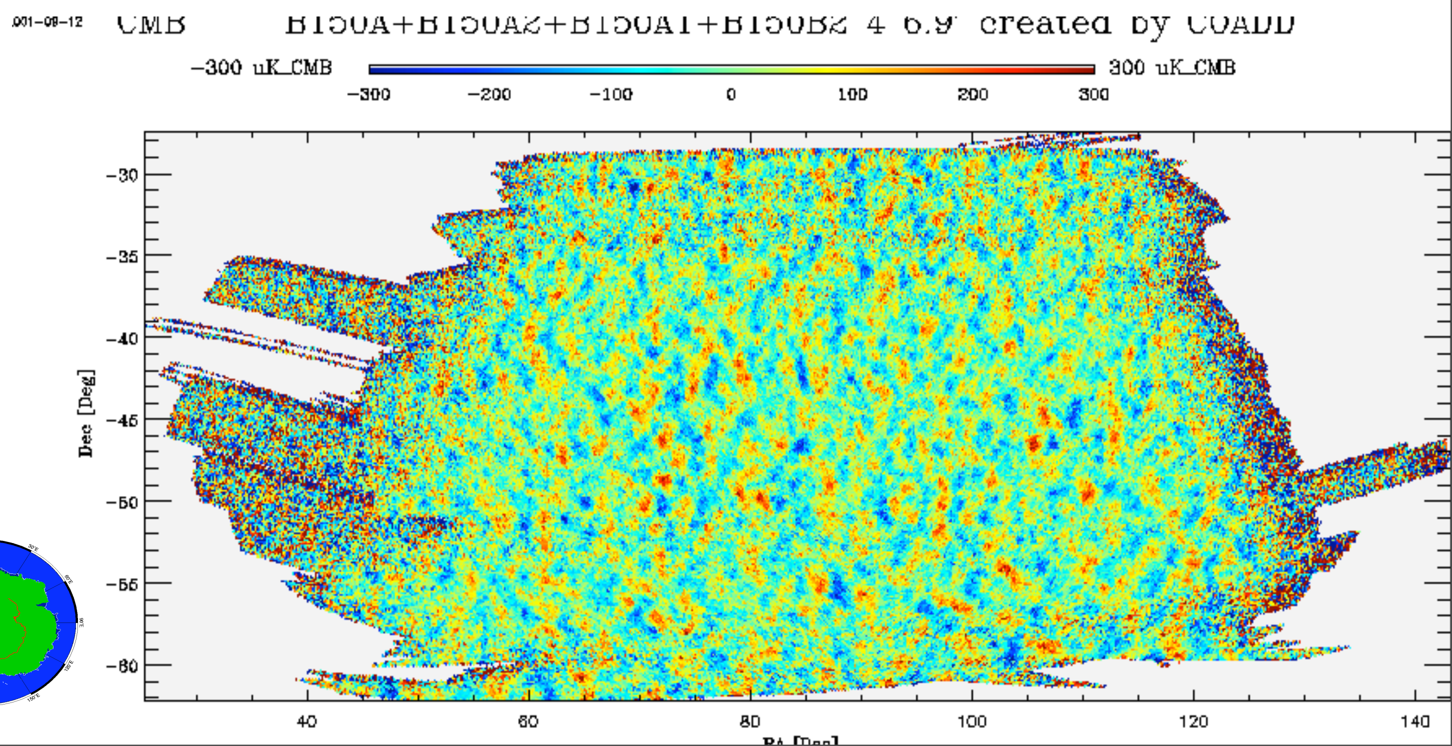
WMAP5

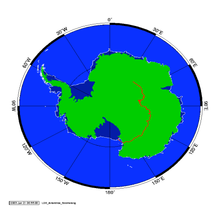
Feb03
Mar06
Mar08

Boomerang @150GHz is (nearly) Gaussian: Simulated vs Real

thermodynamic CMB temperature fluctuations 2.9% of sky $\Delta T \sim 30$ ppm







Random Fields in Early Universe Cosmology

Dick Bond @
CITA ICAT Canadian Institute for Theoretical Astrophysics L'institut canadien d'astrophysique theorique
25 years cifar

What was the Universe made of & how was it distributed?

Are there primordial non-Gaussian compenents - subdominant inflation-induced, preheating -induced or cosmic-string induced?

THEN: coherent inflaton /**"vacuum" energy + zero-point fluctuations** in all fields (*Gaussian RF*) & then preheat via mode coupling to incoherent cascade to thermal equilibrium soup

---

very early U early to middle to now U **very late U**

string theory/landscape/higher dimensions

inflation cyclic baryogenesis dark matter BBN γdec **dark energy**

$V_{eff}(\psi_{inf})$? $V_{eff}(\psi_{inf})$?

$K_{eff}(\psi_{inf})$? $K_{eff}(\psi_{inf})$?

trajectory probability

$-d\ln\rho_{tot}/d\ln a\ /2$
$=\varepsilon(k) = 1+q,\ k\sim Ha$

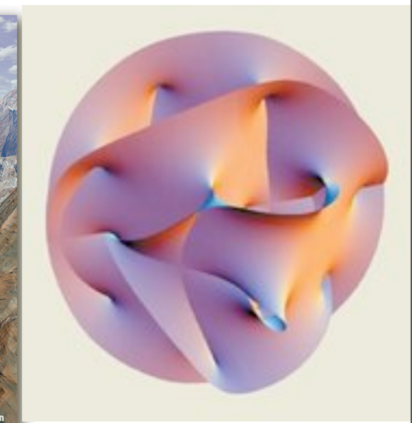
cosmic mysteries

n_b/n_γ ρ_{dm}/ρ_b z_{eq}/z_{rec} ρ_{curv} ρ_{de}/ρ_{dm} $\rho_{de}\sim H^2M^2_{Planck}$ $\rho_{m\nu}/\rho_{stars}$

Old view: Theory prior = delta function of THE correct one and only theory

New view: Theory prior = probability distribution on an energy landscape whose features are at best only glimpsed,

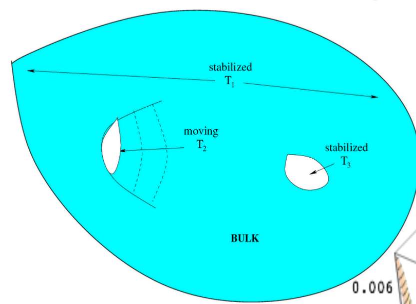
huge number of potential minima, inflation the late stage flow in the low energy structure toward these minima. Critical role of collective coordinates in the low energy landscape:

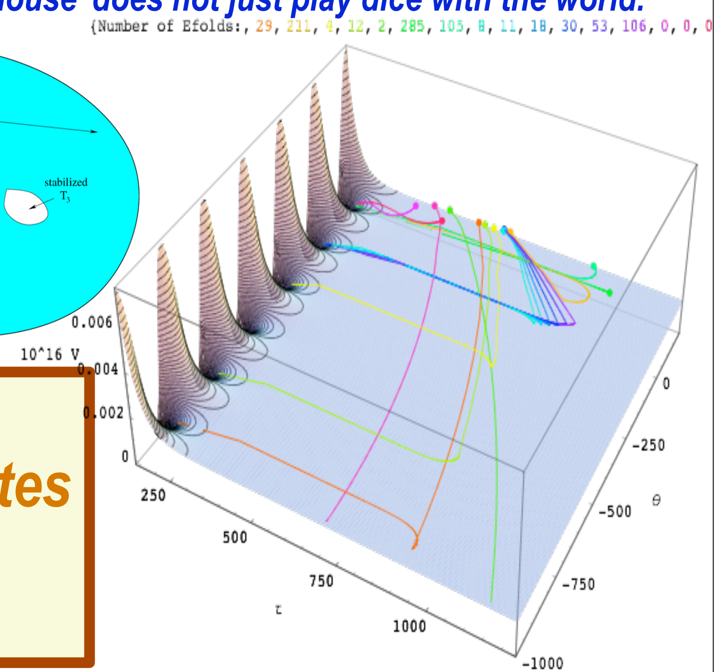


moving brane/antibrane separations (D3,D7) moduli fields, sizes and shapes of geometrical structures such as holes in a dynamical extra-dimensional (6D) manifold approaching stabilization

Roulette inflation Kahler moduli/axion

The 'house' does not just play dice with the world.





theory prior ~ probability of trajectories given potential parameters of the collective coordinates X probability of the potential parameters X probability of initial conditions

Standard Parameters of Cosmic Structure Formation

$\Omega_b h^2$ $\Omega_{dm} h^2$ Ω_Λ Ω_k τ_c $\ln A_s$ n_s $r = A_t/A_s$ $dn_s/d\ln k$ n_t

$1+w_0, w_a$ $\theta \sim \ell_s^{-1}$ $n_e(a)$ $\sim \ln \sigma_8^2$

primordial non-Gaussianity

$\Phi(x) = \Phi_G(x) + f_{NL} (\Phi_G^2(x) - \langle\Phi_G^2\rangle)$

local smooth

DBI inflation: non-quadratic kinetic energy
cosmic/fundamental strings/defects
from end-of-inflation & preheating

$\Phi(x) = \Phi_G(x) + F_{NL}(\chi_b) - \langle F_{NL} \rangle$

resonant preheating

$\ln P_s(\ln k)$ & $r(k_p)$ & $\ln P_t(\ln k)$

+ subdominant isocurvature/ cosmic string/ tSZ ...

Observables and conclusions

$$\Phi(x) = \Phi_G(x) + f_{NL}\,(\Phi_G^2(x) - <\Phi_G^2>)$$

local quadratic non-G constraint: $-9 < f_{NL} < 111 \Rightarrow -4 < f_{NL} < 80$ WMAP5 ($\pm$ 5-10 Planck1yr)

$$\Rightarrow \Phi(x) = \Phi_G(x) + F_{NL}(\chi_b) - <F_{NL}>$$

resonant preheating form

modulated curvature fluctuations from preheating are superimposed on the usual curvature fluctuations from the inflaton

the peak values have $\delta \ln a \sim 10^{-5} \Rightarrow$ comparable to standard Gaussian

temperature fluctuations, but spiky $F_{NL} \Rightarrow$ non-Gaussian?

As long as $g^2/\lambda \leq O(1)$, the χ field has very long wavelength perturbations (similar to, but uncorrelated with, the inflaton field)

Large Scale Structure statistics of spiky F_{NL} mapping: under investigation

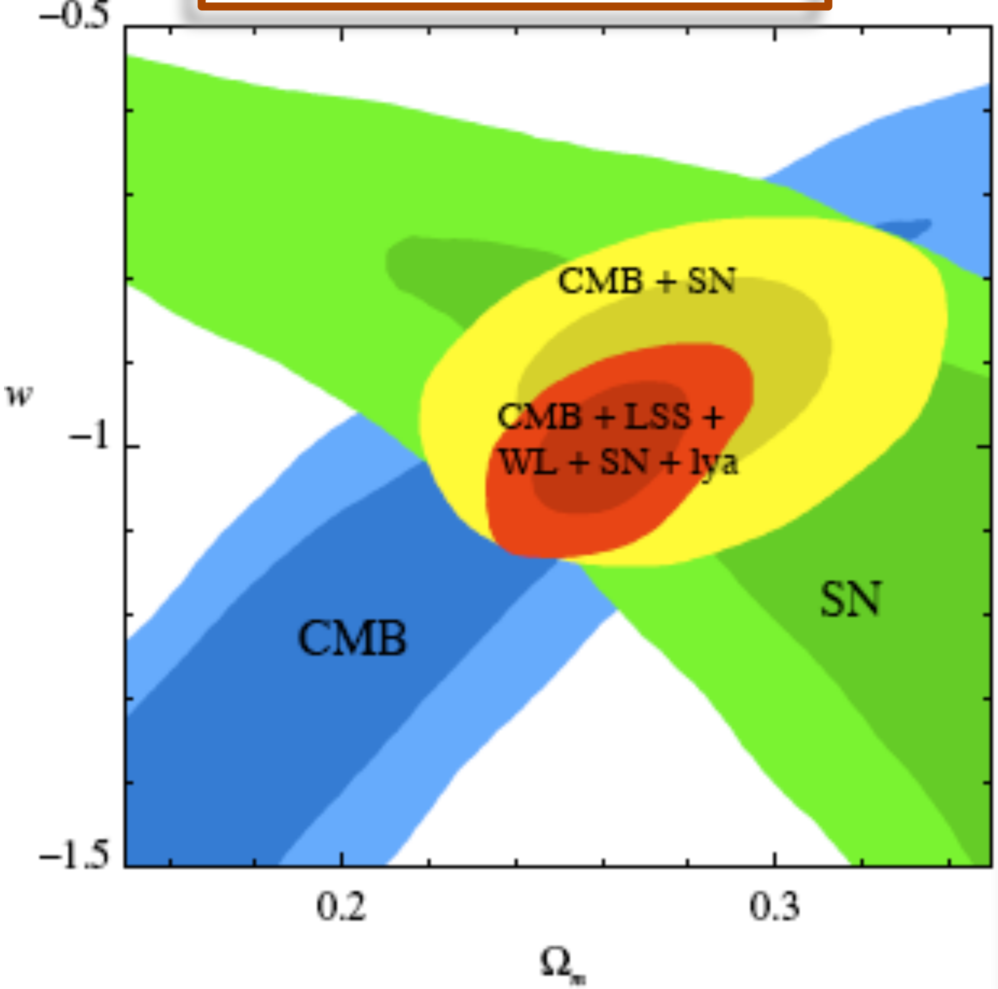
Rich possibilities in theory space & on the sky

e.g., $F_{NL}(\chi) \sim \Sigma_p F_p \exp(-(\chi_p-\chi)^2/2\gamma_p^2) \Rightarrow$ e.g., $<\delta F_{NL}|\chi_{LF}> \sim \Sigma_p \beta_p \chi_{LF}$, but non-G is possible.

INFLATION NOW   *PROBES NOW*

$$w(a) \equiv \frac{p(a)}{\rho(a)}$$

$1+\mathbf{w_0} = -0.0 \pm 0.06$



$\mathbf{w(a)=w_0+w_a(1-a)}$

$1+\mathbf{w_0} = -0.01 \pm 0.19$

$\mathbf{w_a} = 0.0 +0.6-0.8$

piecewise parameterization

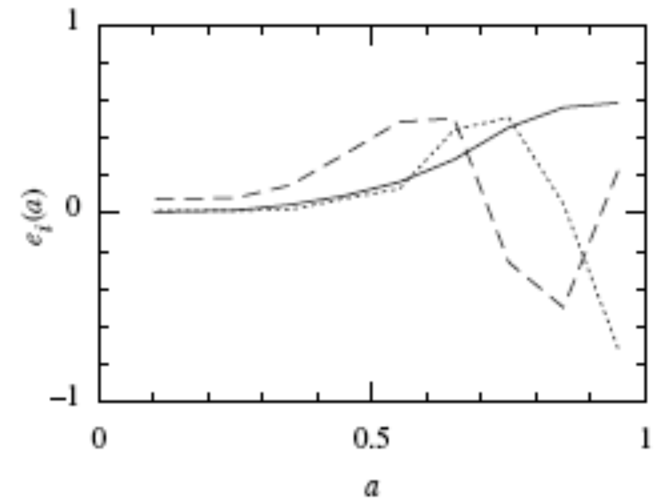
4,9,40 modes in redshift

9 & 40 into Parameter eigenmodes

data cannot determine >2 EOS parameters

DETF Albrecht etal06, Crittenden etal06, hbk08

σ_1**=0.13** σ_2**=0.33** σ_3**=0.58**



. **$\varepsilon_{\phi 0}$ = 0.0 +/- 0.09 if constant, $\varepsilon_{\phi 0}$ = -0.015 +/- 0.3 if a-linear model**

INFLATION NOW

PROBES NOW

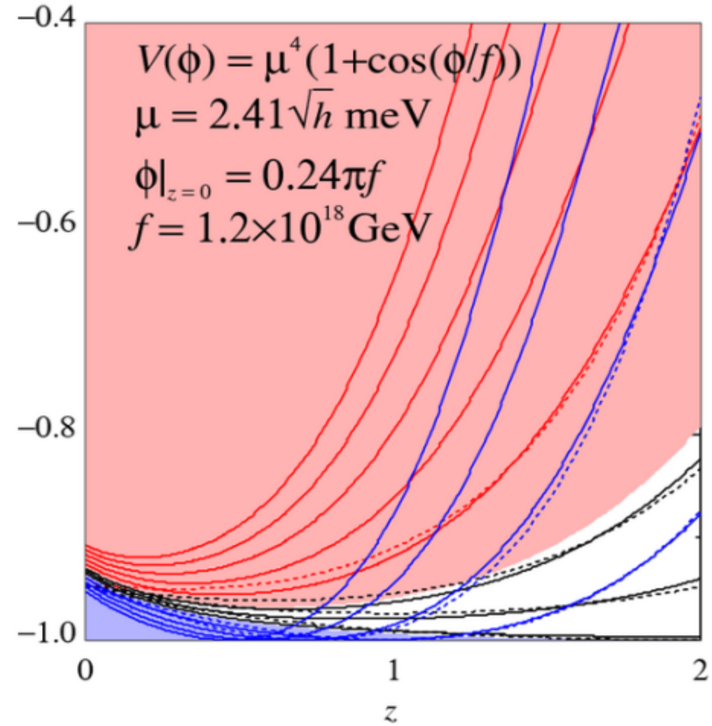
- Cosmological Constant (w=-1)
- Quintessence

  (-1≤w≤1)
- Phantom field

  (w≤-1)
- Tachyon fields

  (-1 ≤ w ≤ 0)
- K-essence

  (no prior on w)



trajectory probability: ~1 e-fold => blind is bad => slow-to-moderate roll ++

$-d\ln\rho_\phi / d\ln a \,/2$

$= \varepsilon_\phi(a) \quad =(1+w)2/3$

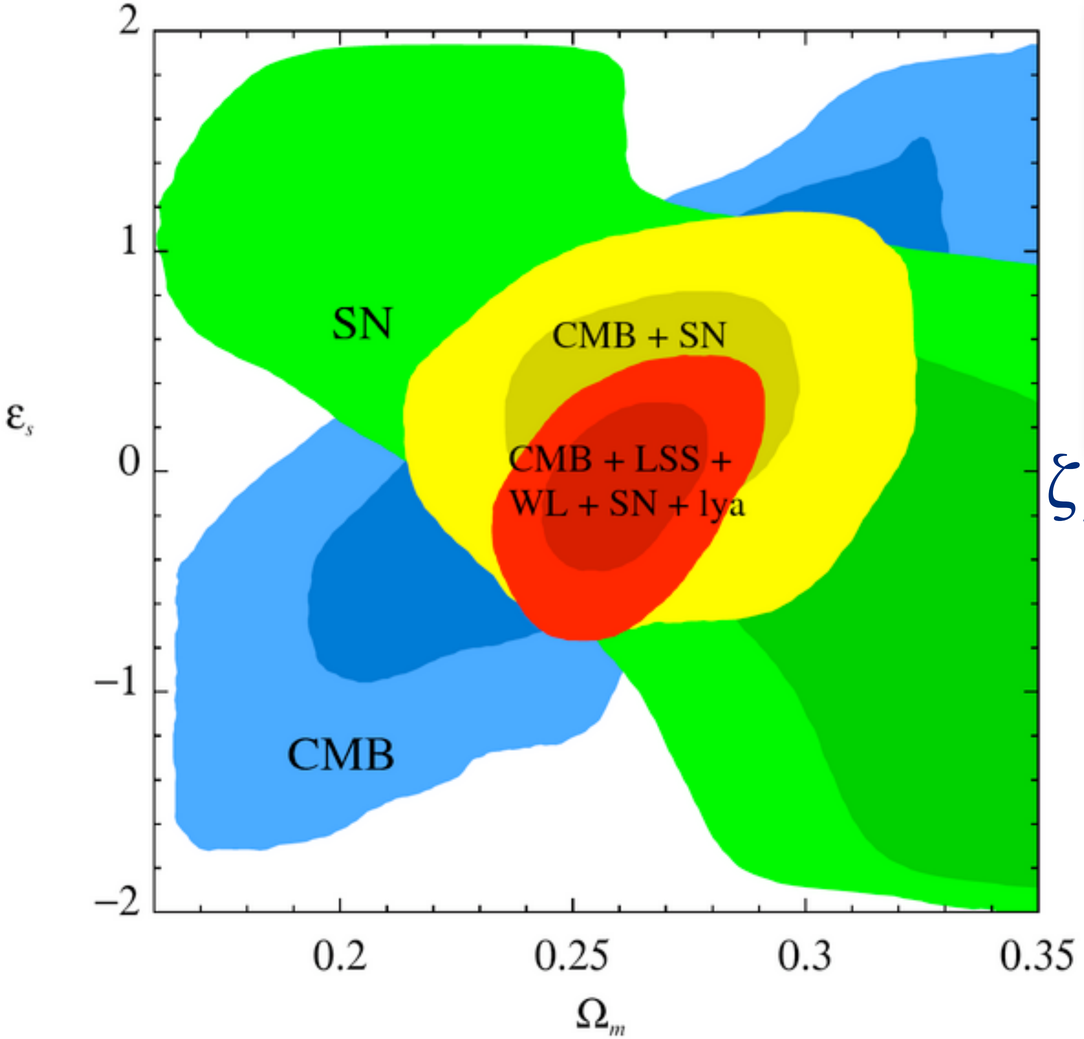
$= \varepsilon_s f(a/a_{\Lambda eq}; a_s/a_{\Lambda eq}; \zeta_s)$

$\varepsilon_s = (d\ln V/d\psi)^2/4$ @pivot a_{eq}

$\zeta_s = +-1.001\, d^2\ln V/d\psi^2 \,/4$ @pivot a_{eq}

$\zeta_s = d\ln\varepsilon_s / d\ln a$ x1/2 @pivot a_{eq}

measuring ε_s ζ_s a_s=0 tracking (SNe$_{union}$+CMB$_{wmap5+acbar+cbi5yr+b03+}$+WL$_{cfhtls+cosmos}$+LSS$_{sdssRG+2dF}$+Lya)



ε_s= (dlnV/dψ)^2/4 @pivot a_{eq}

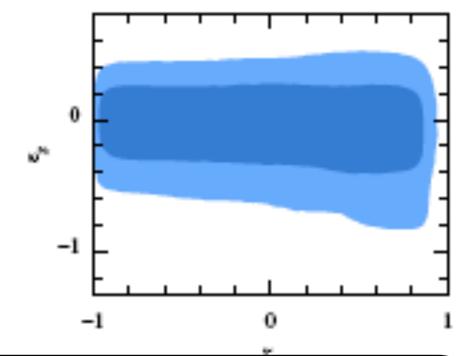
ε_s	.01 + .25 -.28	1
	-.03 + .21 -.25	3
	-.03 + .26 -.30	**2**

ζ_s= +-1.001d^{2}lnV/dψ^2 /4 @pivot a_{eq}

ζ_s =dlnε_s /dlna x1/2 @pivot a_{eq}

ill-determined now

$0.1^{+0.6}_{-0.7}$



cannot reconstruct the quintessence potential, just the slope ε_s & ~hubble drag

Beyond Einstein panel: LISA+JDEM

Forecast: **JDEM-SN** (2500 hi-z + 500 low-z)

+ **DUNE-WL** (50% sky, gals @z = 0.1-1.1, 35/min^2) + **Planck1yr**

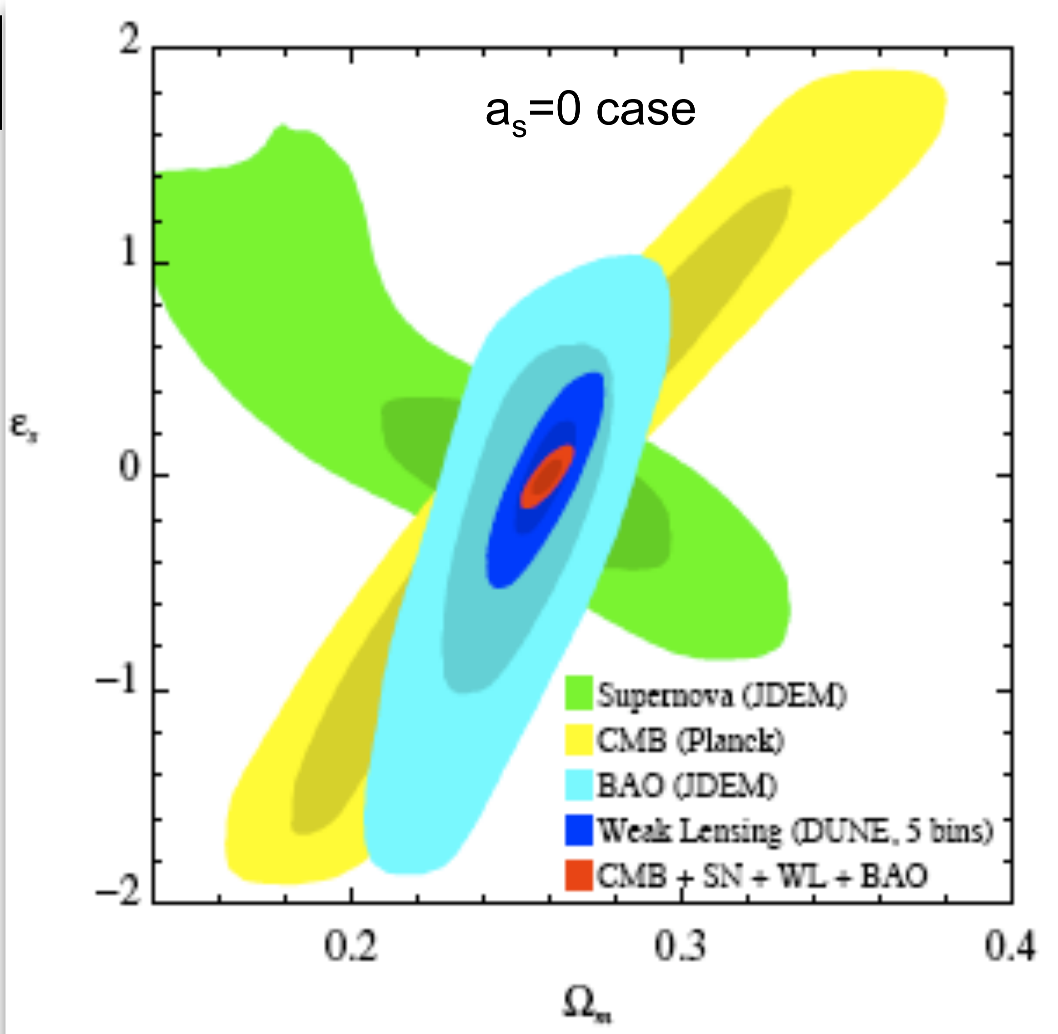
now ESA /Eucid ESA (+NASA/CSA)

INFLATION NOW

PROBES THEN

$\varepsilon_s = 0.00^{+0.07}_{-0.06}$

ζ_s ~dlnε_s /dlna /2 $0.1^{+0.6}_{-0.7}$



cannot reconstruct the quintessence potential, just the slope ε_s & ~hubble drag

end2

FLUCTUATION GENERATOR → **LINEAR AMPLIFIER** → **NONLINEAR DISSIPATIVE AMPLIFIER**

statistically homogeneous & isotropic Gaussian Random Fields => 2-point power spectra fns of 3D wavenumber $|\mathbf{k}|$

gastro-physics

aka “sub-grid” aka astronomy

nonlinear objects of various types & their clustering properties, N-point statistics

quantum noise

$P_\Phi(k)$, $P_{GW}(k)$

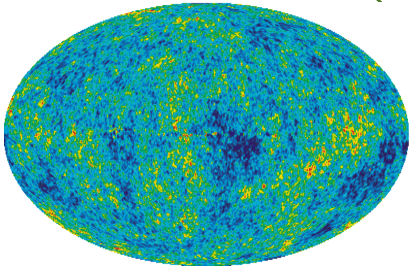
$\Delta T_{(LM)}$

$P_\rho(k)$, $P_{\mathbf{v}}(k)$

$P_{gal}(k)$, $P_{cl}(k)$

n_{gal} n_{cl} ..

n_{halos} n_{peaks}



Cosmic Microwave Background Radiation

statistically isotropic all-sky GRF on the 2-sphere

$C_L = \langle|\Delta T_{(LM)}|^2\rangle$, $k_{2D} \sim L + 1/2$

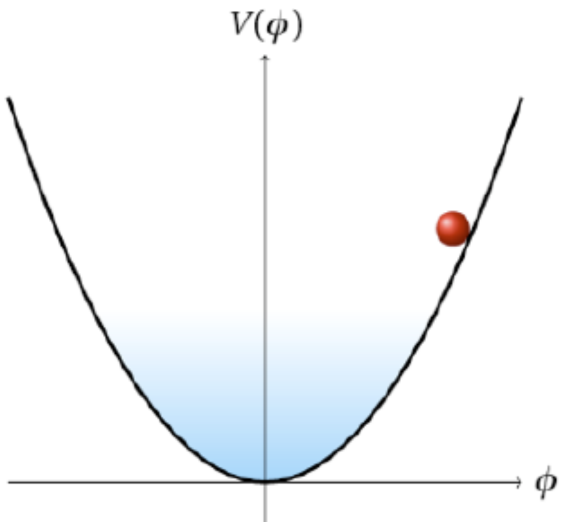
preheating

Parametric resonance

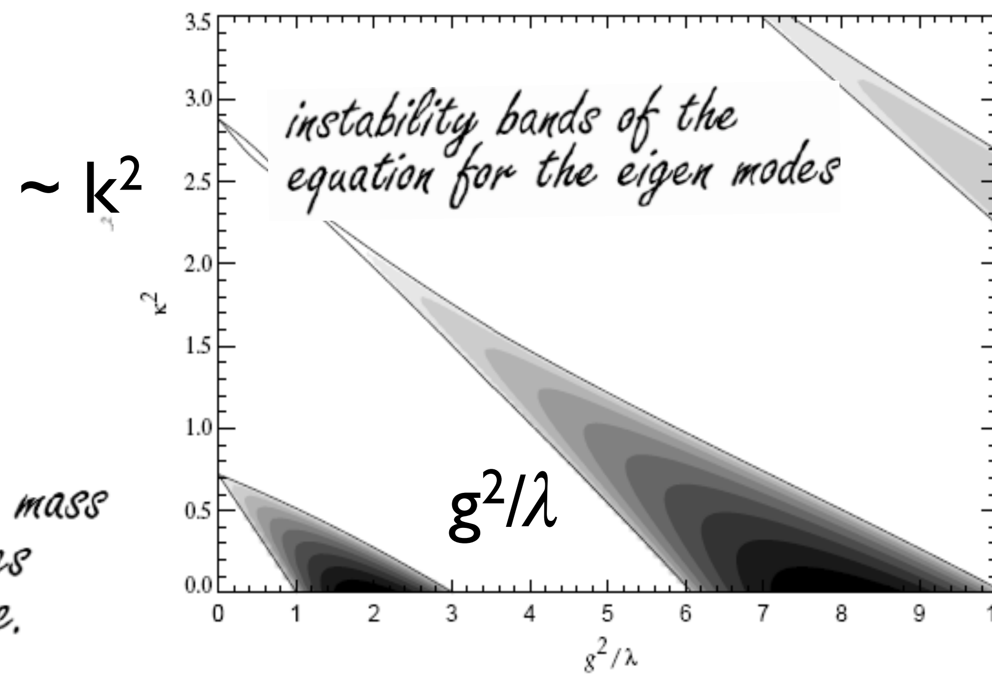
$V(\phi,\chi) = 1/4\ \lambda\ \phi^4 + 1/2\ g^2\ \phi^2\ \chi^2$

90s Kofman, Linde, Starobinsky, .., Greene, Felder, Frolov, ... 00s

$$\ddot{\chi}_k + 3\frac{\dot{a}}{a}\dot{\chi}_k + \left(\frac{k^2}{a^2} + g^2\phi^2\right)\chi_k = 0$$



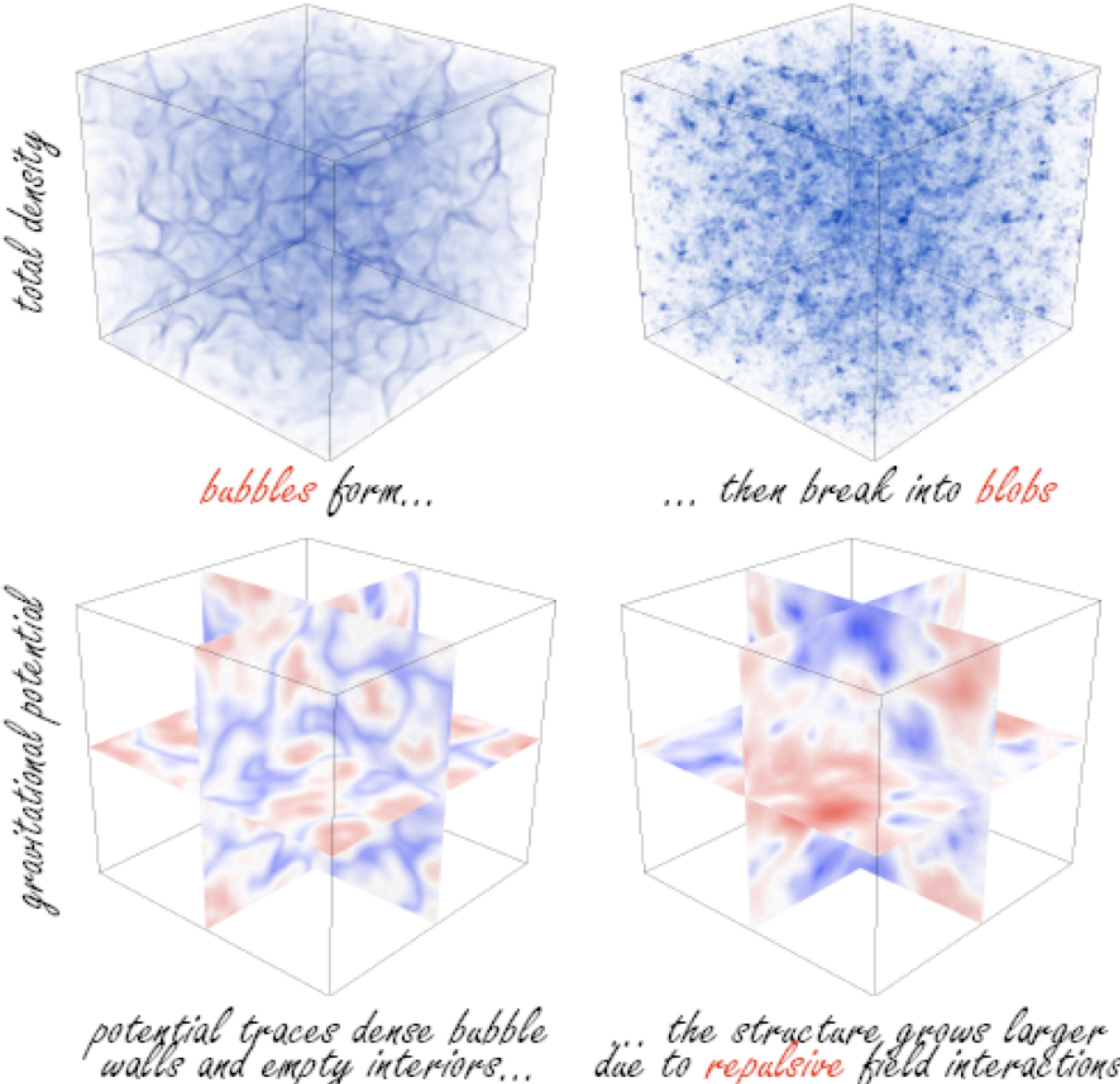
The oscillating inflaton modulates the mass of the fields coupled to it, and becomes unstable through parametric resonance.

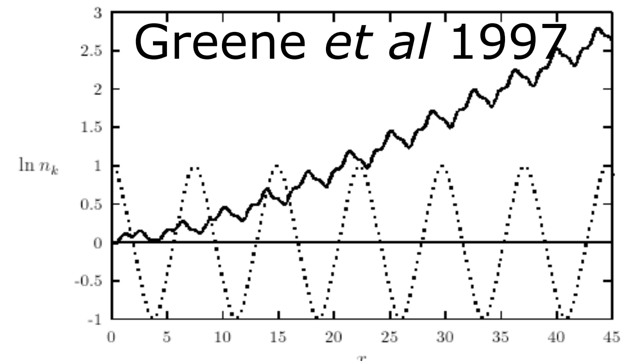


Formation of Structure

Linear instability amplifies seed fluctuations and creates structure; its non-linear evolution looks like LSS but is driven by repulsion!

Frolov 2008 DEFROST code ≈ Felder's LatticeEasy





Bond, Andrei Frolov, Zhiqi Huang, Kofman 09:

results depend upon the input value of a uniform χ_b, a random Gaussian variable with variance $\sim H_b/2\pi$

(uncorrelated with inflaton $\delta\phi \sim H_b/2\pi$ fluctuations)

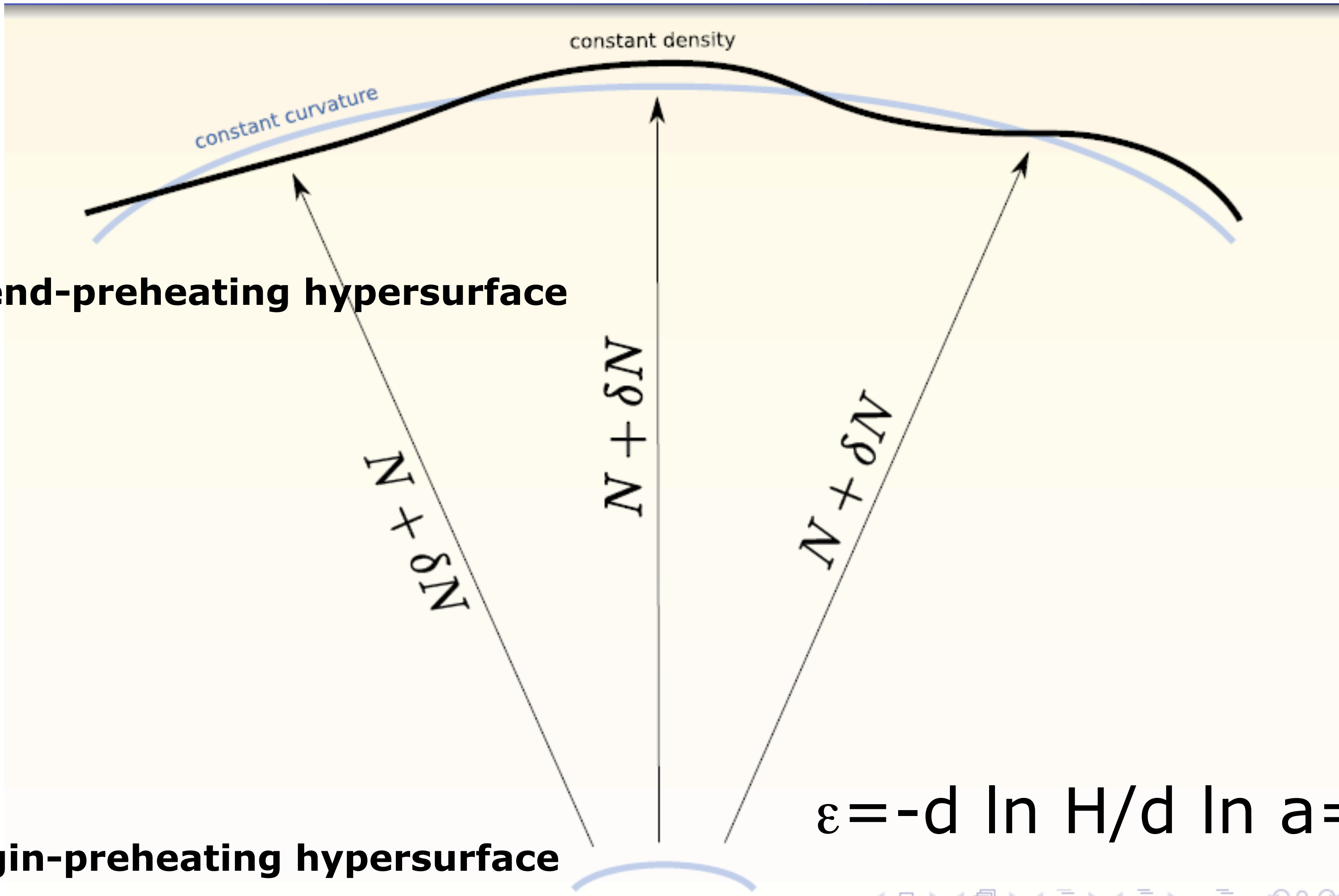
non-Gaussianity from preheating

$\chi_b(x,t) + \chi_f$

Bond, Andrei Frolov, Zhiqi Huang, Kofman 09:

calculate how the time from the end of accelerated expansion (end of inflation) to the onset of thermal equilibrium depends on $\chi_b(x,t)$

$$-\delta N = \delta \ln a|_H = \textit{curvature fluctuation}$$



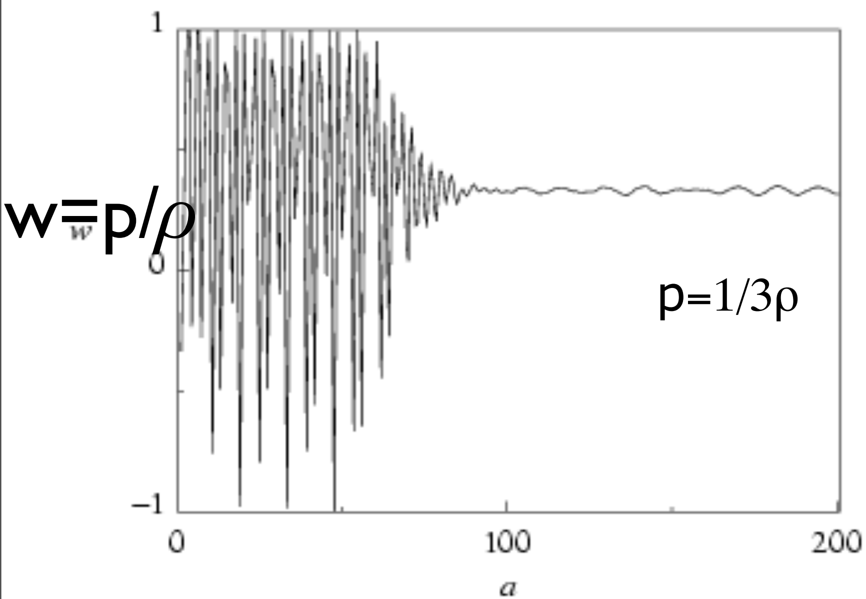
end-preheating hypersurface

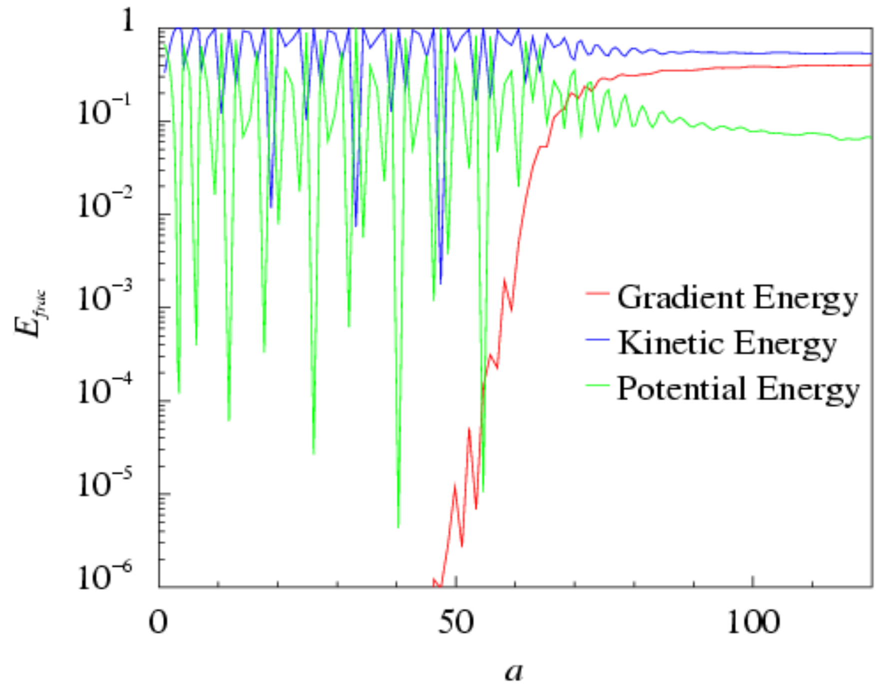
begin-preheating hypersurface

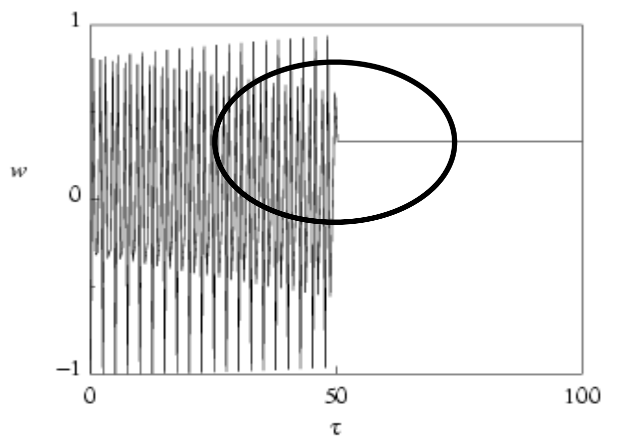
$\varepsilon = -d \ln H / d \ln a = 1$

equation of state evolution via simulation: pass from w ≈ -1 potential-dominated coherence via oscillation & mode cascade to w=1/3 thermal equilbrium

simulation size 128^3 $\chi_b = 0$







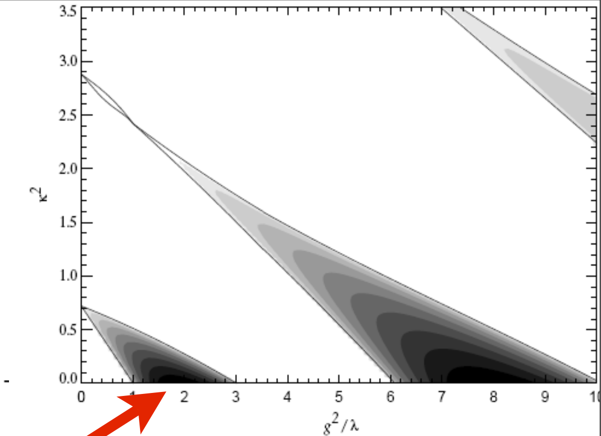
We search for ppm effects

⇒ Symplectic DEFROST:

energy conservation ~10^{-13} level!!

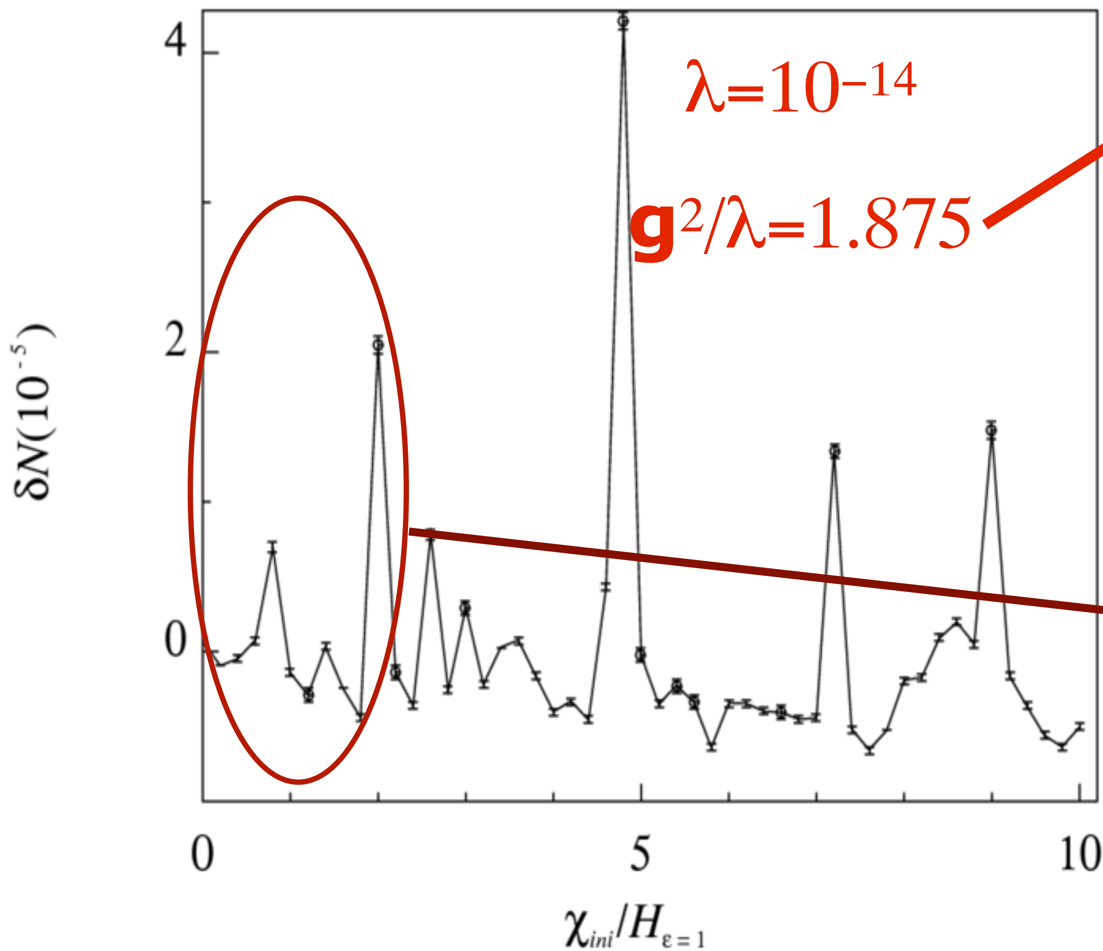
cf. DEFROST ~10^{-5} level & Felder's LatticeEasy ~10^{-4} level.

$\delta \ln a(\chi_b)$ modulation: response to varying $\chi_b(x,t_e)$

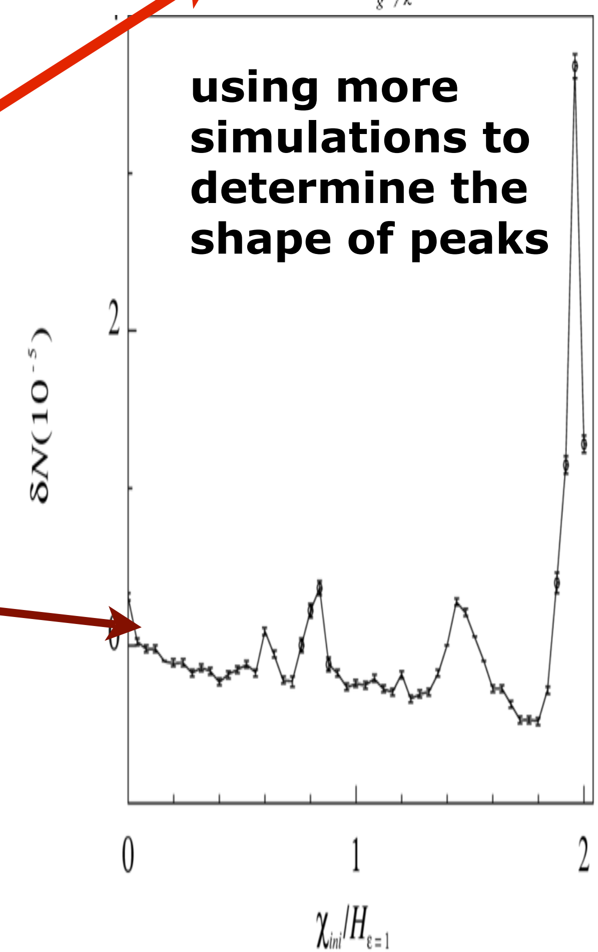


$\lambda=10^{-14}$

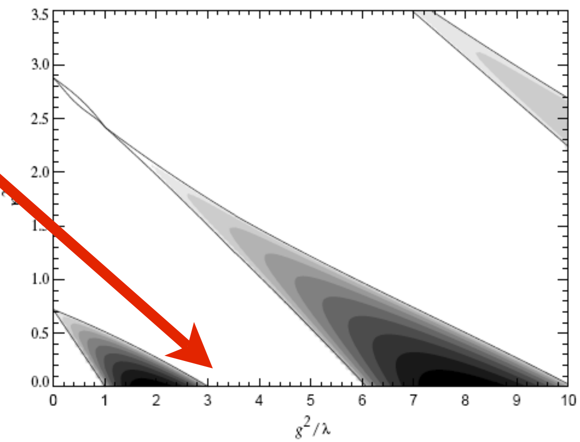
$g^2/\lambda=1.875$

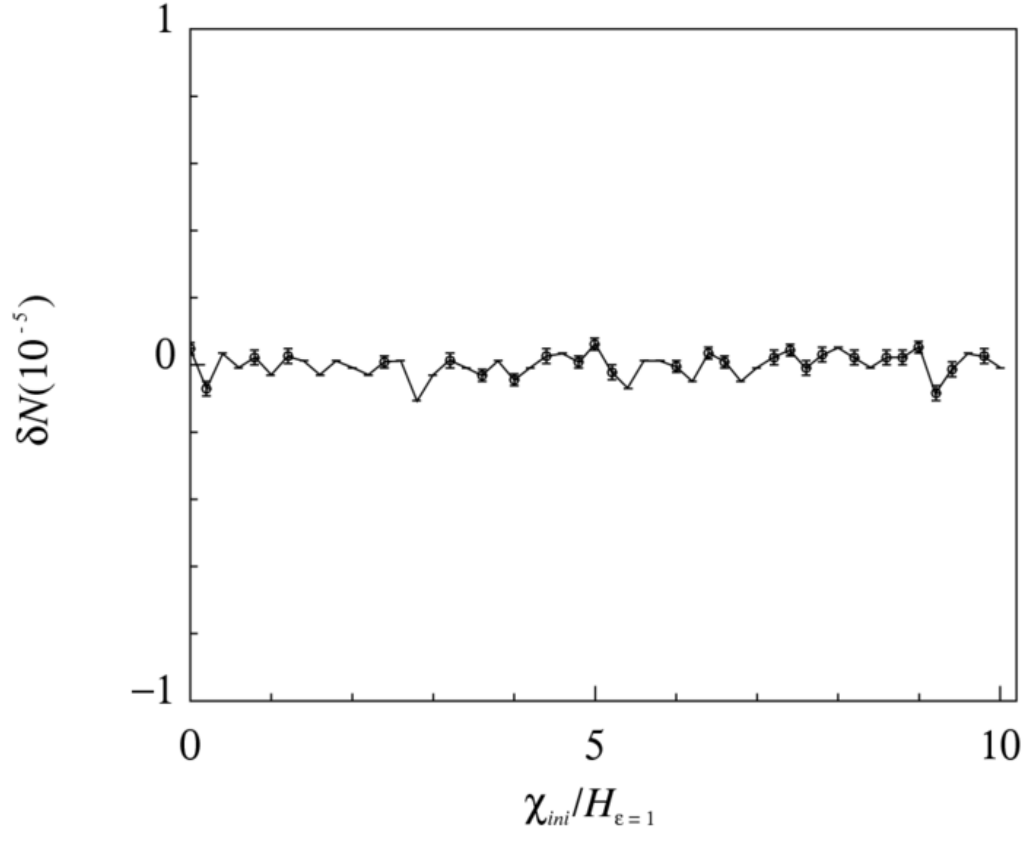


using more simulations to determine the shape of peaks



if the k=0 mode is not in the parametric resonance bands ($g^2/\lambda=3$ example) then δln a is not modulated by χ_b





Other tests: UV and IR cutoffs ok ➔

END

CITA ICAT Canadian Institute for Theoretical Astrophysics L'institut canadien d'astrophysique theorique — **Dick Bond** CIAR 25 years cifar

Constraining Trajectories of Dark Energy Inflatons

Inflation Now $\varepsilon_\phi(a) = \varepsilon_s f(a/a_{\Lambda eq}; a_s/a_{\Lambda eq}; \zeta_s)$

$\varepsilon_\phi = -d\ln\rho_\phi / d\ln a / 2$ ~0 now, to $\varepsilon = -d\ln\rho_{tot} / d\ln a / 2$ ~0 to 2, 3/2, ~.4

cf. w(a): w0,wa; w in z-bands or z-modes; $\varepsilon(a)$: in modes, jerk

~1 good e-fold. only ~2 params. priors matter

Inflation Then $\varepsilon(k) = (1+q)(a)$ **= mode expansion in resolution (lnHa ~ lnk)**
~r/16 (Tensor/Scalar Power & gravity waves) ~ 10 good e-folds CMB+LSS

Cosmic Probes Now CMB(Apr08), CFHTLS SN(Union 307),WL, LSS/BAO, Lyα

Cosmic Probes Then JDEM-SN + DUNE-WL + Planck1

Zhiqi Huang, Bond & Kofman 09 $\varepsilon_s = -0.03 \pm 0.28$ now, inflaton (potential gradient)^2

to +-0.07 then Planck1+JDEM SN+DUNE WL, weak a_s < 0.36 now <0.21 then

3-parameter formula

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$$

+ Friedmann Eqn+DM+B

$$\theta \equiv \begin{cases} \sin^{-1} \frac{\dot{\phi}}{\sqrt{2\rho_\phi}} \\ \sinh^{-1} \frac{\dot{\phi}}{\sqrt{2\rho_\phi}} \end{cases}$$

$$w(a) = \quad -1 + \frac{2\epsilon_s}{3}\{\frac{(\frac{a_s}{a})^{3-3.6a_s|\epsilon_s|(1-\Omega_{m0})}}{\sqrt{1+\frac{\epsilon_s}{3|\epsilon_s|}(\frac{a_s}{a})^{6-7.2a_s|\epsilon_s|(1-\Omega_{m0})}}}\frac{1}{\sqrt{|\epsilon_s|}}$$

$$+[\sqrt{1+(\frac{a_{eq}}{a})^3} - (\frac{a_{eq}}{a})^3 \ln((\frac{a}{a_{eq}})^{\frac{3}{2}} + \sqrt{1+(\frac{a}{a_{eq}})^3})](1-\zeta_s)$$

$$+0.36\varepsilon_s(1-\Omega_{m0})\frac{(\frac{a}{a_{eq}})^2}{1+(\frac{a}{a_{eq}})^4}[0.9 - 0.7\frac{a}{a_{eq}} - 0.045(\frac{a}{a_{eq}})^2]$$

$$+\frac{2\zeta_s}{3}[\sqrt{1+(\frac{a}{a_{eq}})^3} - 2(\frac{a_{eq}}{a})^3(\sqrt{1+(\frac{a}{a_e}})^3 - 1)]\}^2$$

accurate fits to **slow-to-moderate roll** & even wild rising baroque late-inflaton trajectories + **thawing & freezing** trajectories.
non-oscillating

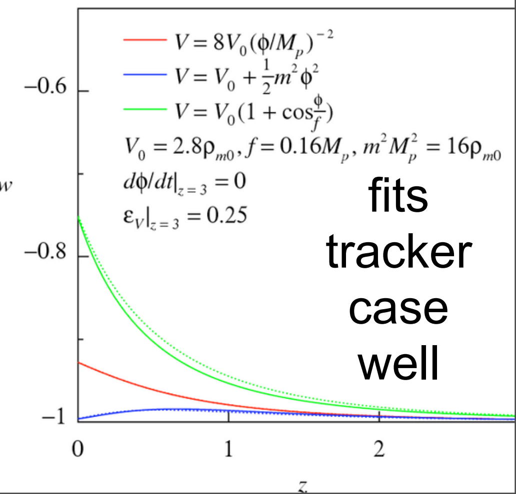
where

$$a_{eq} \equiv (\frac{\Omega_{m0}}{1-\Omega_{m0}})^{\frac{1}{3[1-0.36\varepsilon_s(1-\Omega_{m0})]}}$$

$$a_s \geq 0$$

- ~15% thawing, 8% freezing, with flat priors

$$\sqrt{|\epsilon_V|} = \sqrt{|\epsilon_s|}[1+\zeta_s((\frac{a}{a_{eq}})^{\frac{3}{2}} - 1)] \quad -1 < \zeta_s < 1$$



very early U early to middle to now U **very late U**

inflation *string theory/landscape/higher dimensions* **dark energy**

$V_{eff}(\psi_{inf})$? partial shape reconstruction reconstruct gradient $V_{eff}(\psi_{inf})$?

$K_{eff}(\psi_{inf})$? $K_{eff}(\psi_{inf})$?

$1-n_s \sim 2\varepsilon_s + 4\zeta_s$ x.999 & $r \sim 16\varepsilon_s$ slow roll

2 solutions: nearly uniform acceleration & small ζ_s

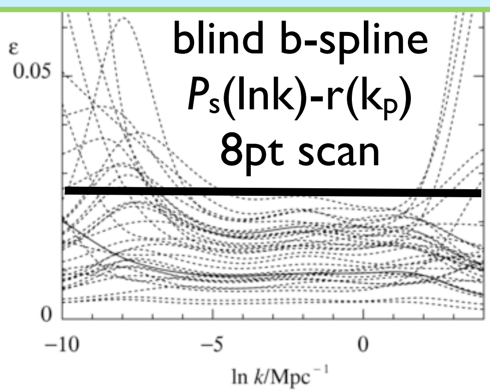
$\varepsilon_s \sim .017 \pm .007$; $\varepsilon_s < .025$ 95% from r

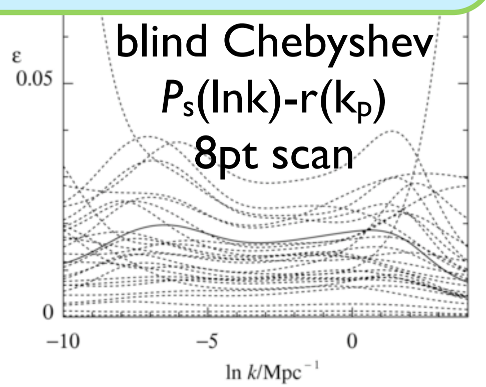
\

low energy inflation with tiny ε_s

$2\zeta_s \sim .017 \pm .007$

errors go to $\pm .0012$ Planck+JDEM+DUNE





$\varepsilon_s = (d\ln V/d\psi)^2/4$ @a_{eq}

$\varepsilon_s \sim -.03 + .26 - .30$

to $\pm .07$ Planck+JDEM+DUNE

$\zeta_s = \pm 1.001\, d^2\ln V/d\psi^2/4$ @a_{eq}

$\zeta_s \sim 0.1 + .6 - .7$

to $+.6-.7$ Planck+JDEM+DUNE **LCDM**

to $+.3-.3$ steep-ish $\exp[-\psi]$

very early U early to middle to now U **very late U**

inflation *string theory/landscape/higher dimensions* **dark energy**

$V_{eff}(\psi_{inf})$? partial shape reconstruction reconstruct gradient $V_{eff}(\psi_{inf})$?

$K_{eff}(\psi_{inf})$? $K_{eff}(\psi_{inf})$?

$1-n_s \sim 2\varepsilon_s + 4\zeta_s$ **x.999 &** $r \sim 16\varepsilon_s$ **slow roll**

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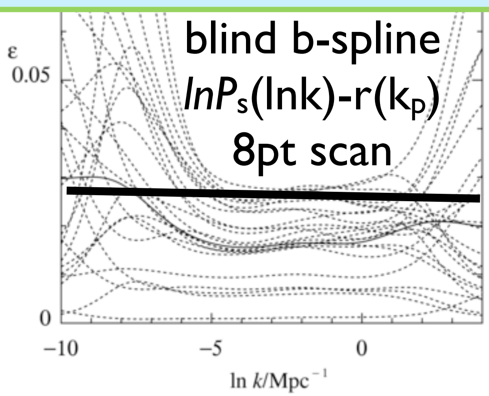
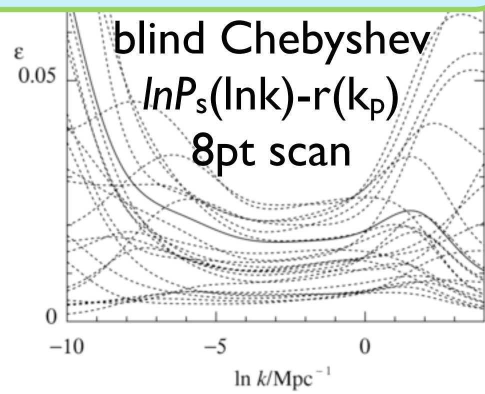
$\zeta_s = +- 1.001\, d^2\ln V/d\psi^2/4$ @a_{eq}

$\zeta_s \sim 0.1 +.6 -.7$

to +.6−.7 Planck+JDEM+DUNE **LCDM**

to +.3−.3 steep−ish exp[−ψ]





very early U early to middle to now U **very late U**

inflation *string theory/landscape/higher dimensions* **dark energy**

$V_{eff}\ (\psi_{inf})$? partial shape reconstruction reconstruct gradient $V_{eff}\ (\psi_{inf})$?

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$1-n_s \sim 2\varepsilon_s + 4\zeta_s$ **x.9999 &** $r \sim 16\varepsilon_s$ **slow roll**

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low energy inflation with tiny ε_s

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errors go to +− .0012 Planck+JDEM+DUNE

$\varepsilon_s = (d\ln V/d\psi)^2/4$ @a_{eq}

$\varepsilon_s \sim -.03 + .26 -.30$

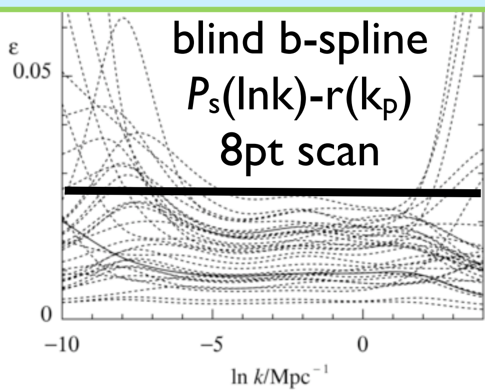
to +− .07 Planck+JDEM+DUNE

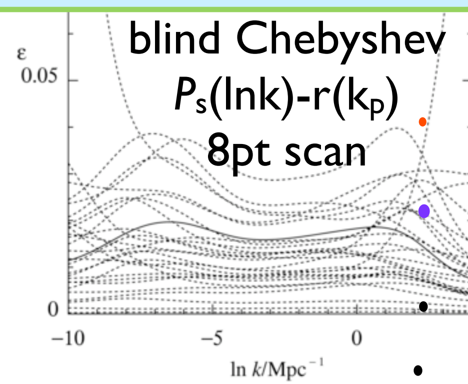
$\zeta_s =_{+-} 1.001\, d^2\ln V/d\psi^2/4$ @a_{eq}

$\zeta_s \sim 0.1 +.6 -.7$

to +.6-.7; +-.3 Planck+JDEM+DUNE

$a_s < 0.36$ ($z_s > 2.0$) • to a_s to <0.21 ($z_s > 3.7$)



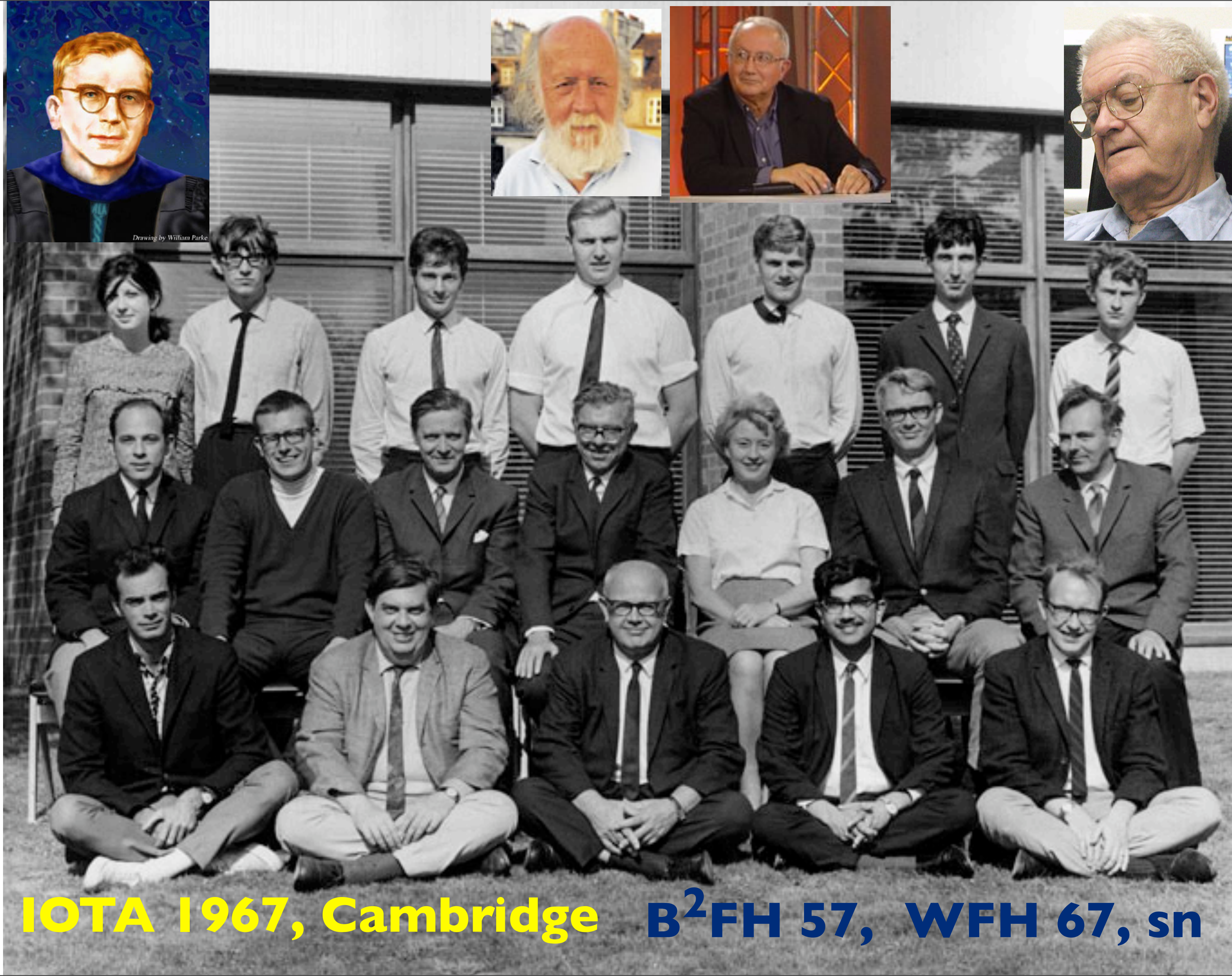


we ignore z_dec and z_bbn constraints on Ω_Q **(a)**
much further trajectory extrapolation needed.

prior sensitivity sqrt(ε): ε=0.00 +.09-.13 &
ε>0 (since phantom is ~ baroque): ε=0.00+.20

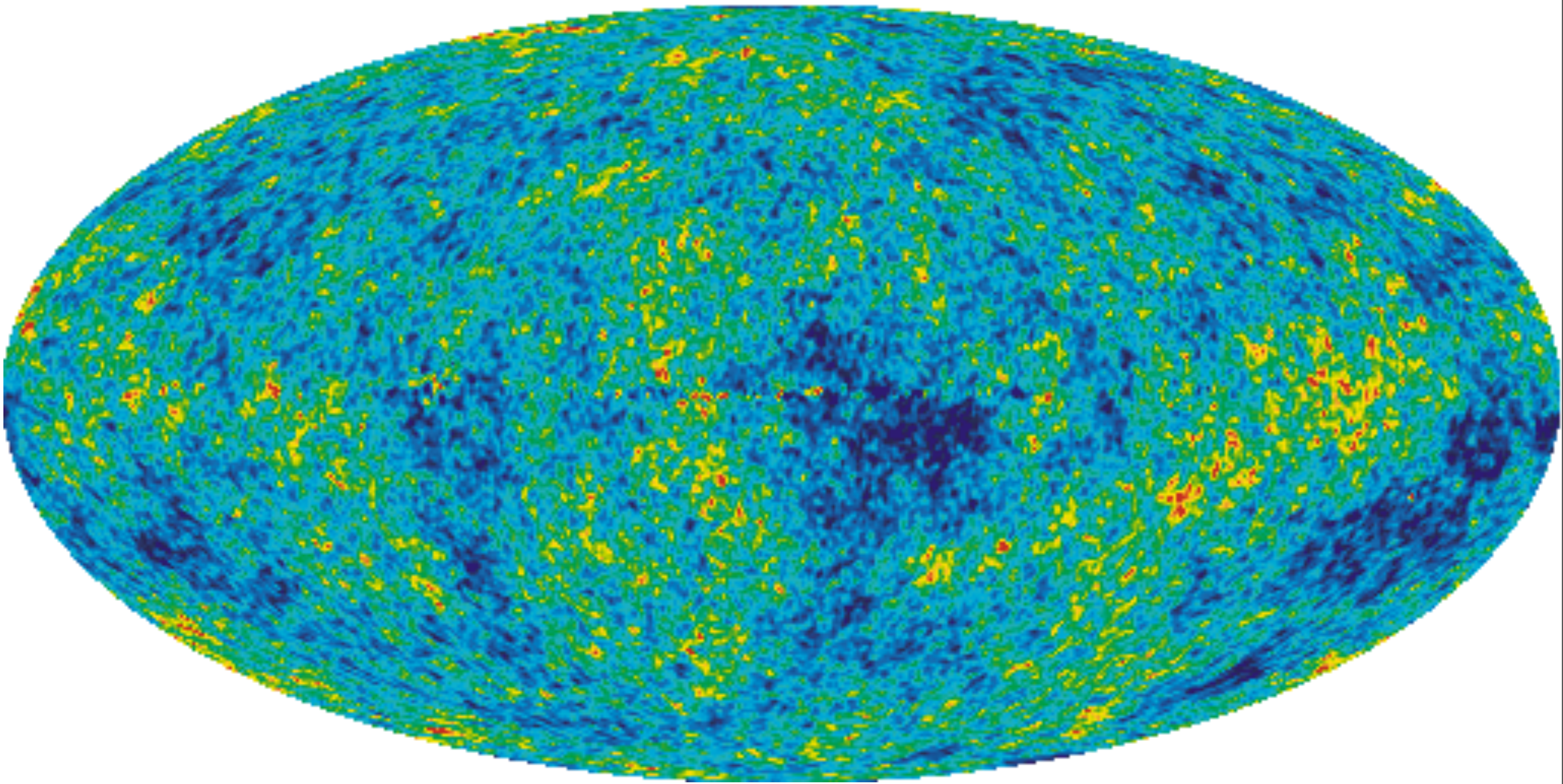
late-inflaton field is < Planck mass

coupled-DE 5th force constraints are strong


Drawing by William Parke
IOTA 1967, Cambridge
B^2FH 57, WFH 67, sn

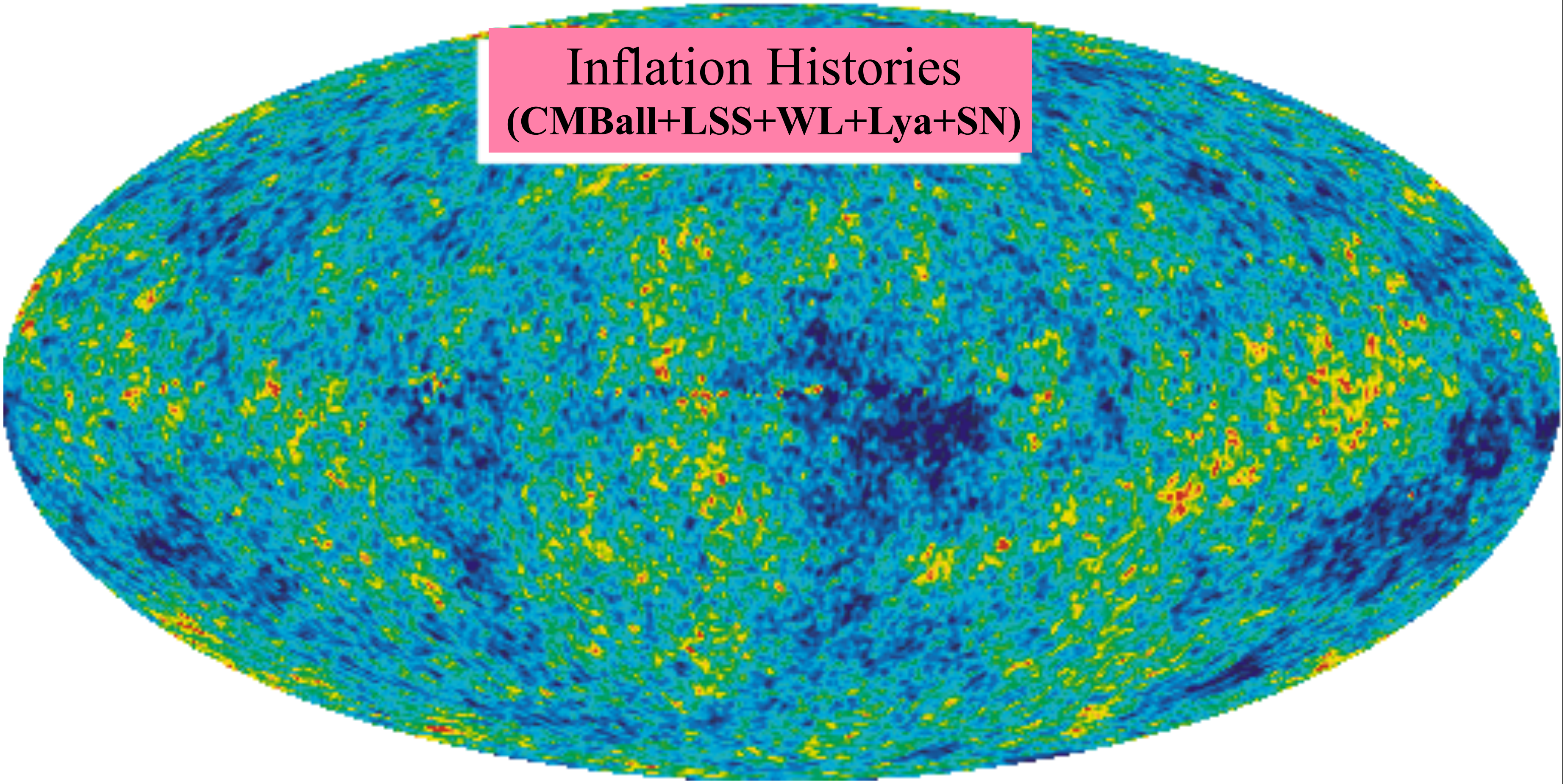
CMBology

Probing the linear & nonlinear cosmic web



CMBology

Probing the linear & nonlinear cosmic web



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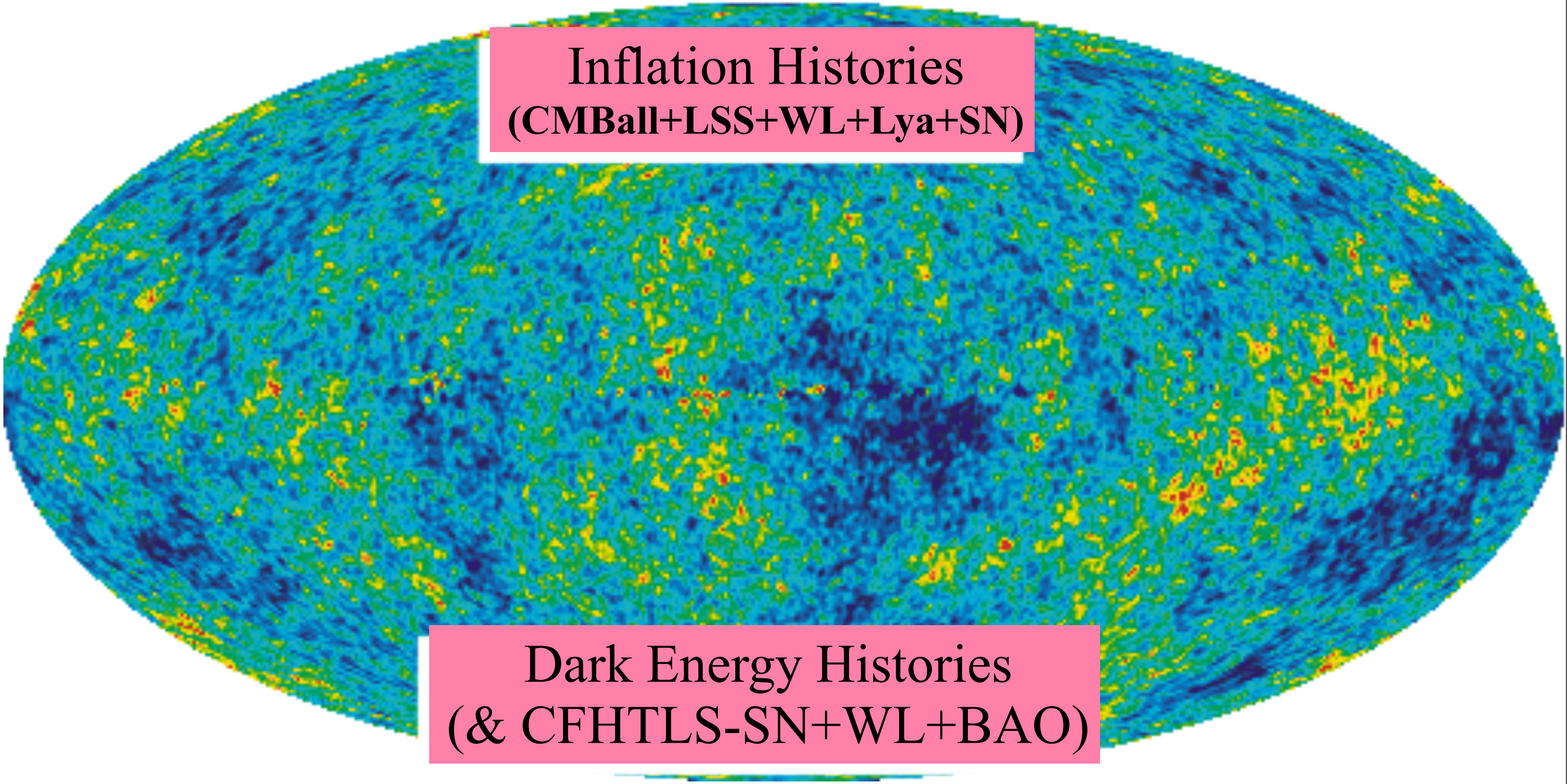

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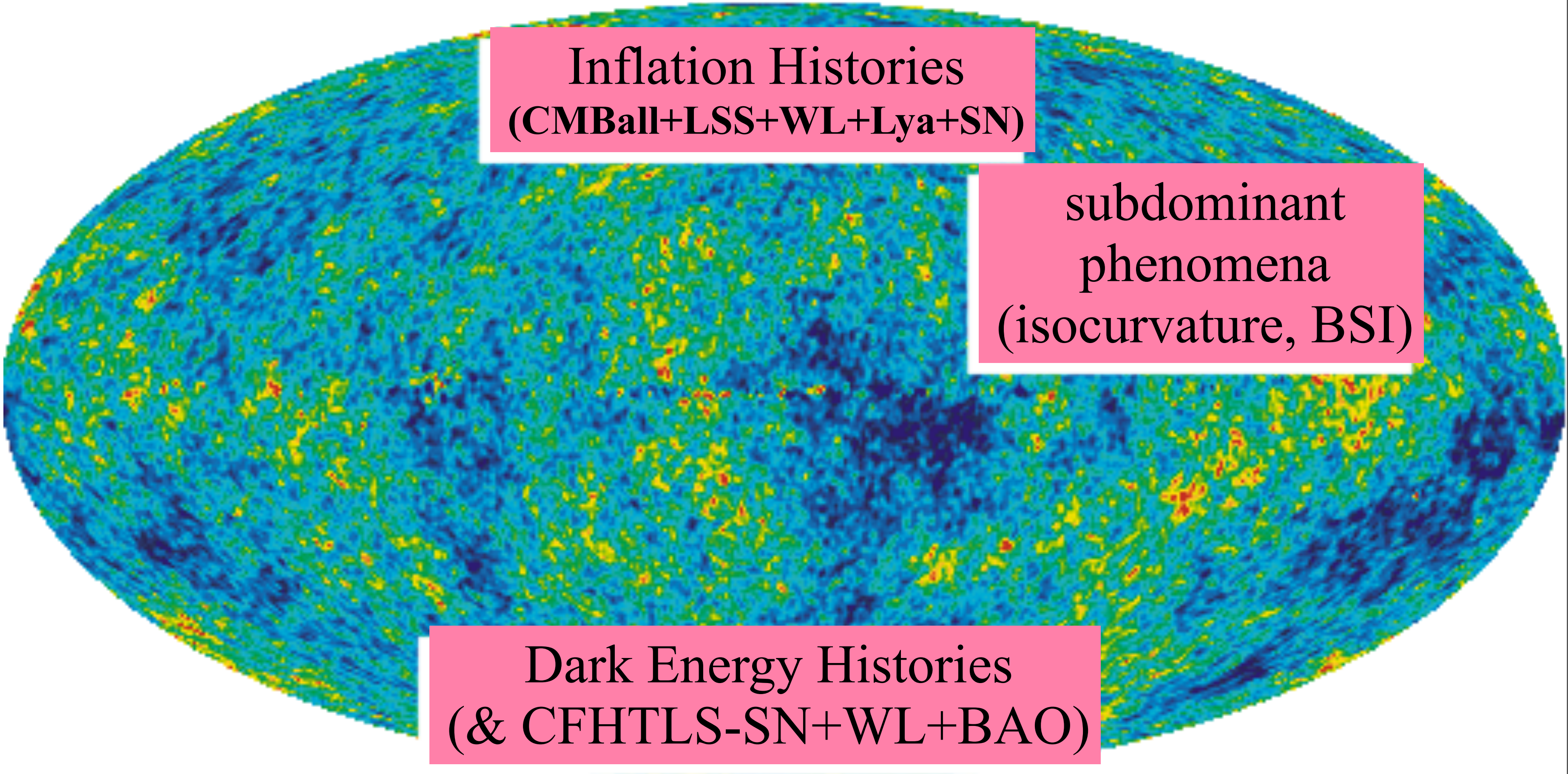

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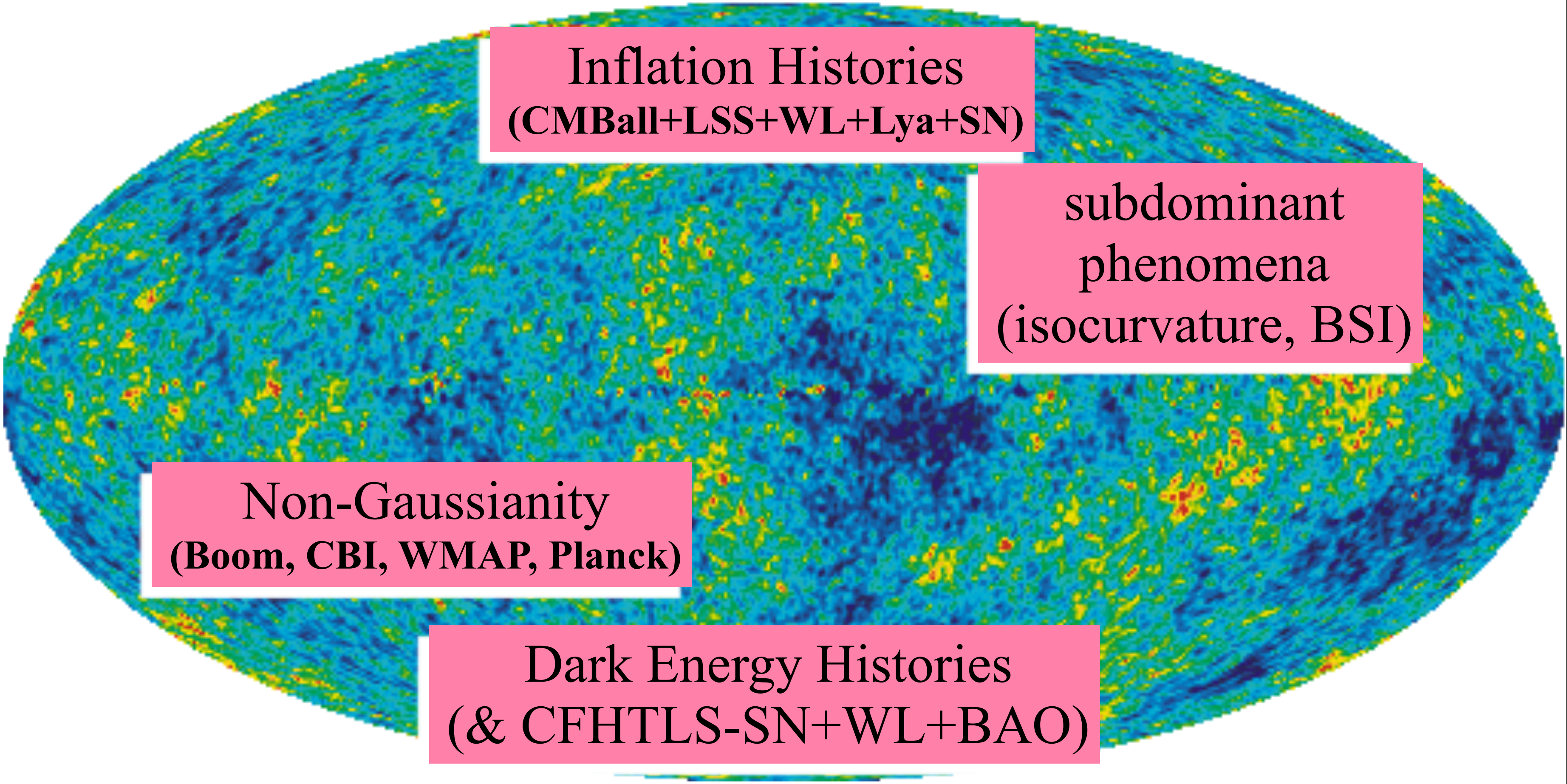

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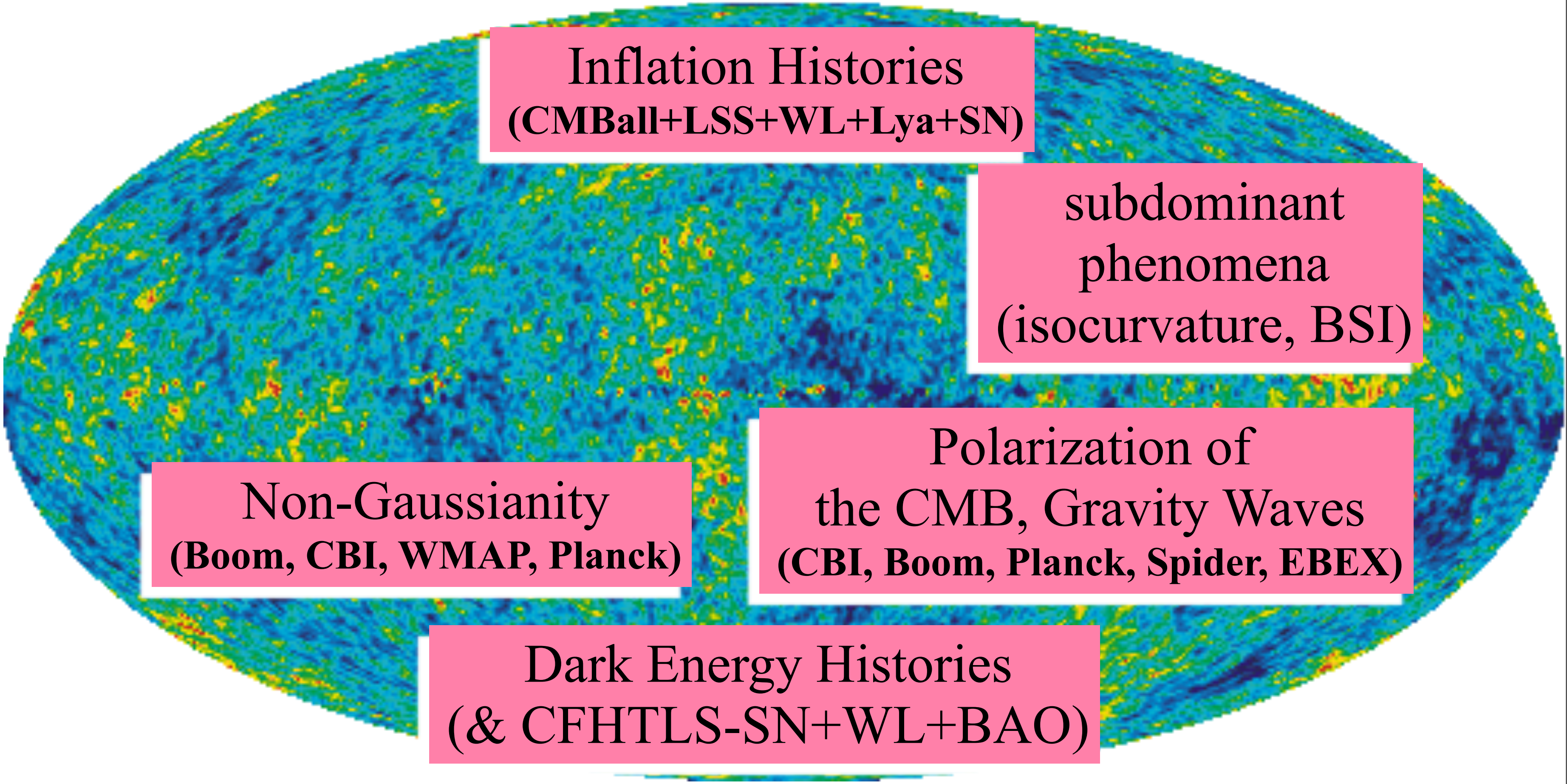
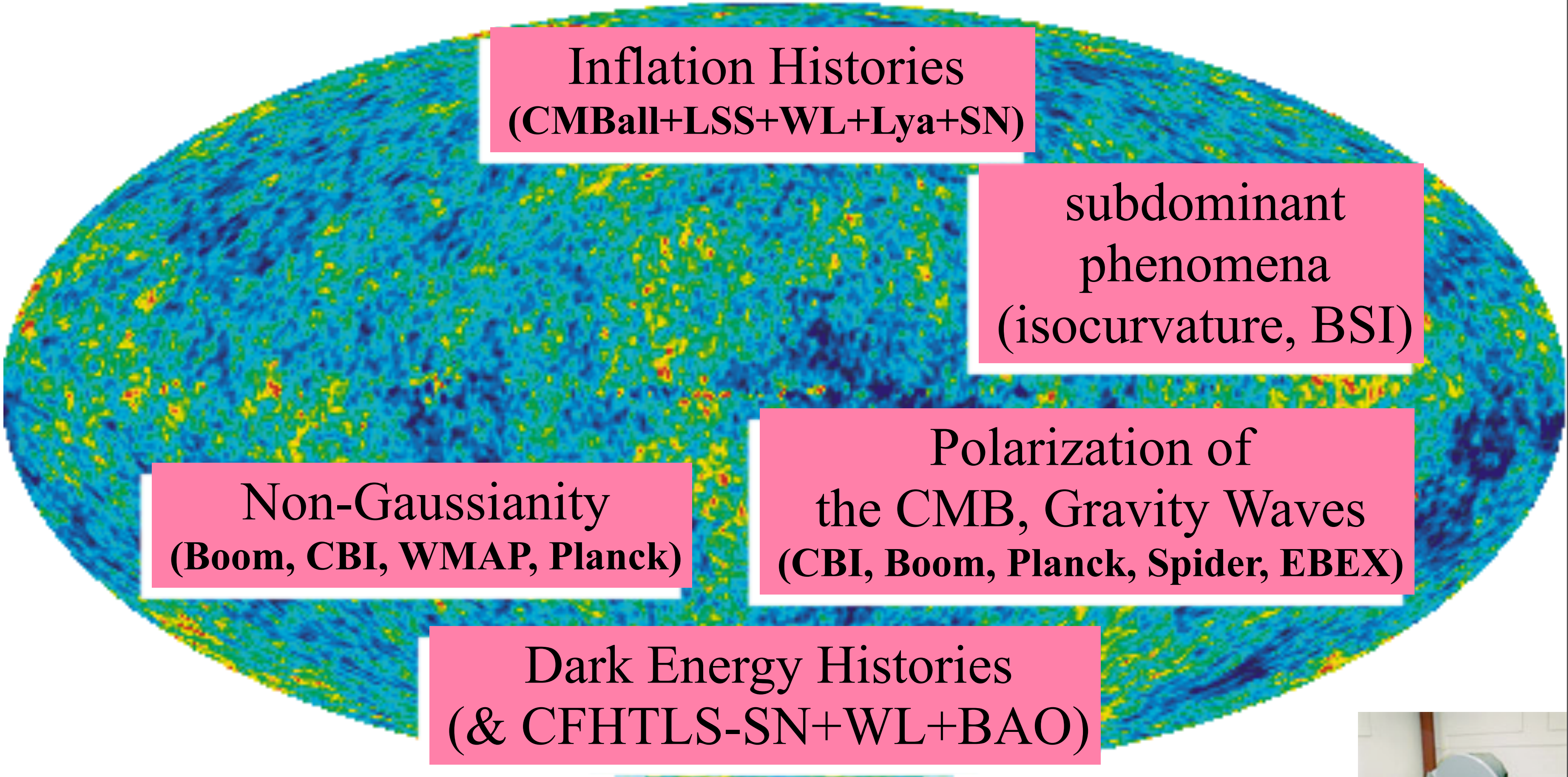
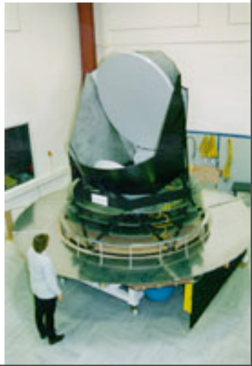
Probing the linear & nonlinear cosmic web



CMBology

Probing the linear & nonlinear cosmic web





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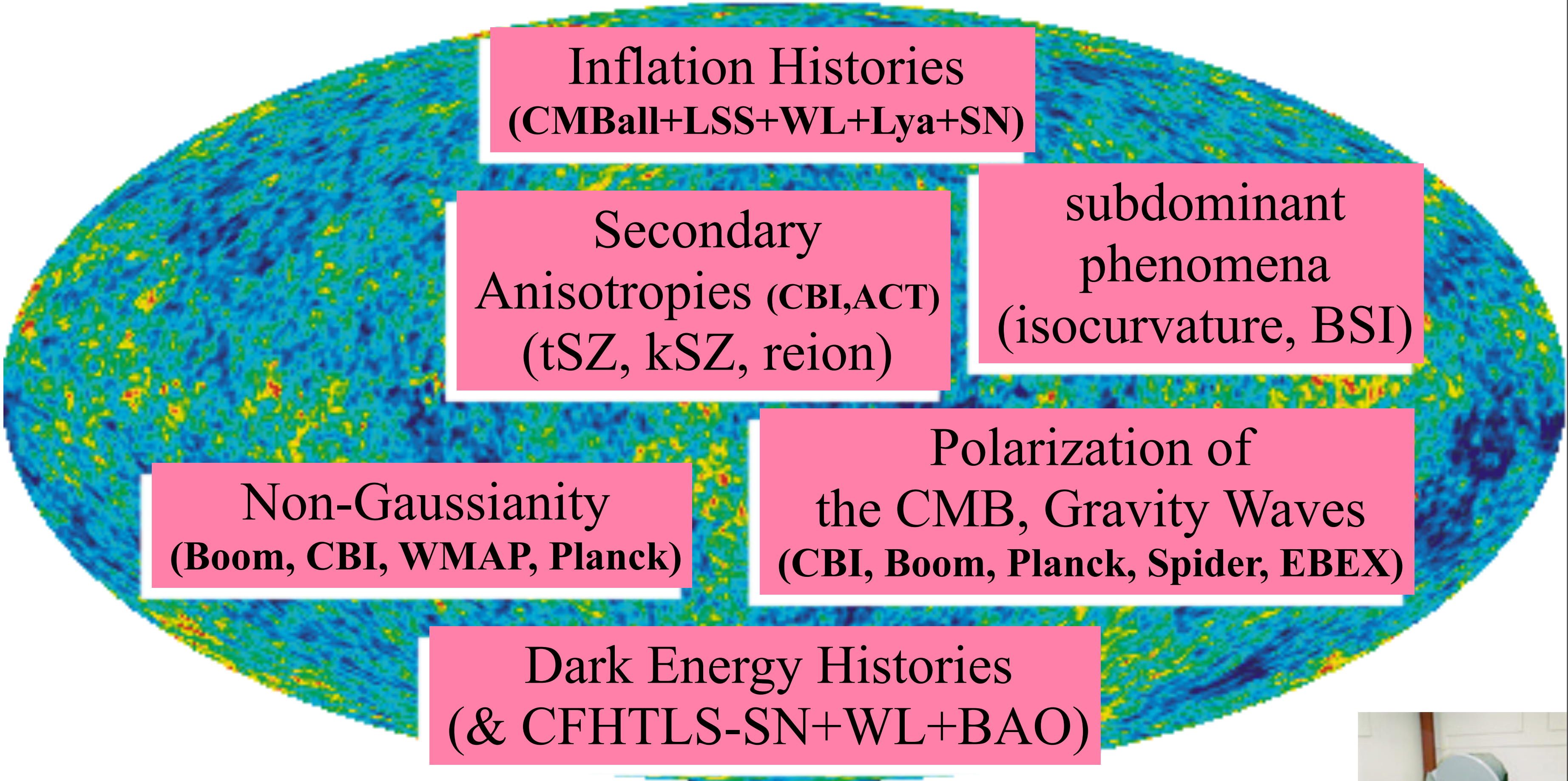
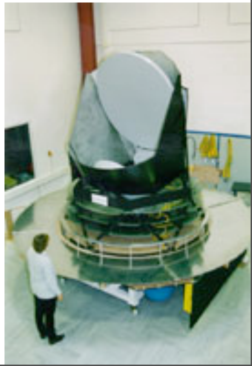
Probing the linear & nonlinear cosmic web





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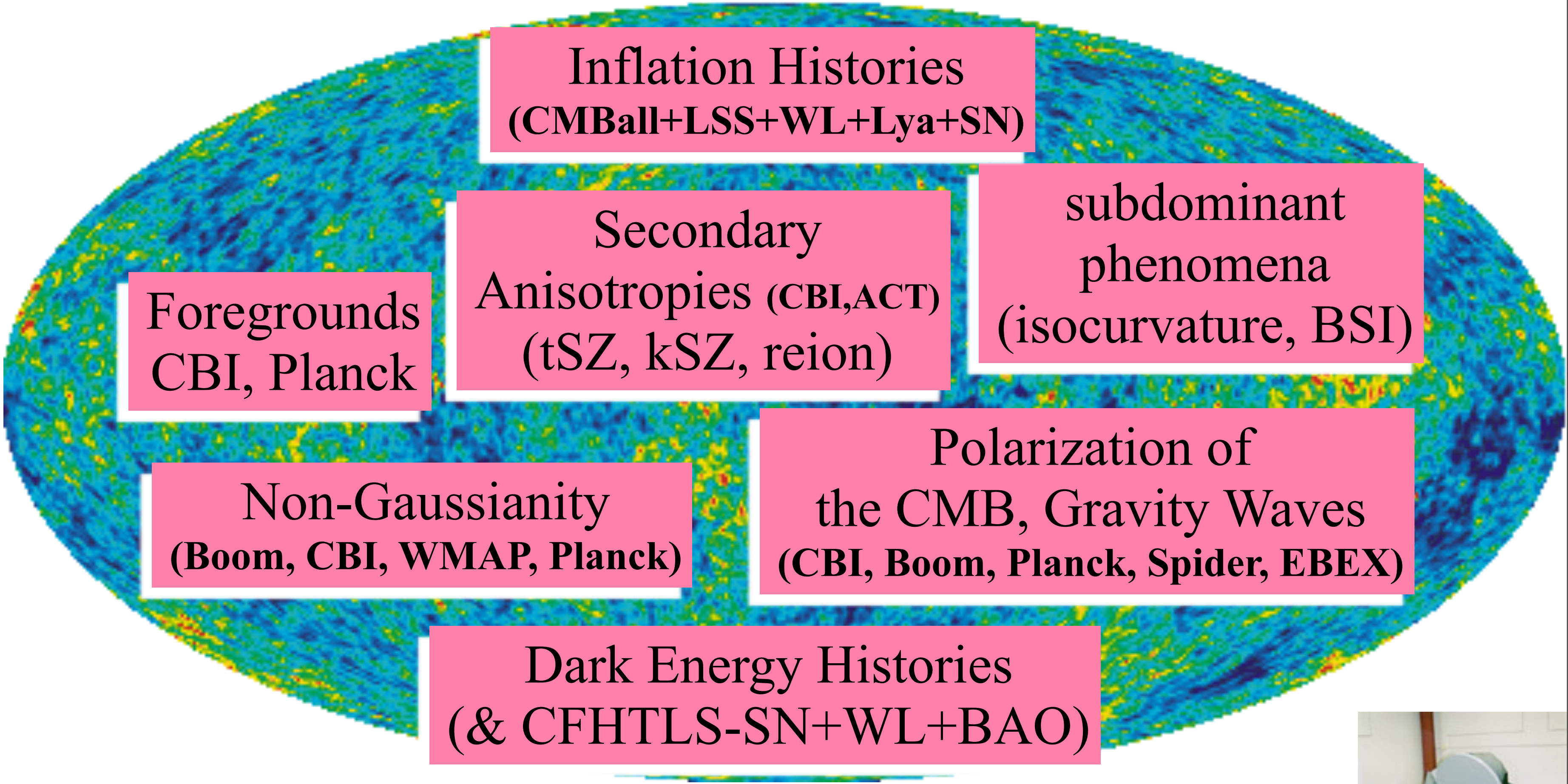
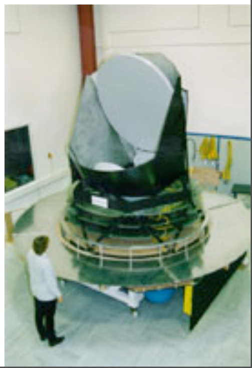
Probing the linear & nonlinear cosmic web





Standard Parameters of Cosmic Structure Formation

$\theta \sim \ell_s^{-1}$ $\sim \ln \sigma_8^2$

Ω_k $\Omega_b h^2$ $\Omega_{dm} h^2$ Ω_Λ τ_c $\ln A_s$ n_s $r = A_t / A_s$

$1+w_0$, w_a $dn_s / d\ln k$ n_t

New Parameters of Cosmic Structure Formation: early-inflaton & late-inflaton trajectories

$\varepsilon_\phi = (1+w(a))\times 3/2$ $\epsilon(k), \quad k \approx Ha$ $\ln H(k_p)$

$\varepsilon_s f(a/a_{\Lambda eq}; a_s/a_{\Lambda eq}; \zeta_s)$ $\ln P_s(k)$ $\ln P_t(k)$

+ subdominant isocurvature/cosmic string/ tSZ ...

CMB Polarization, Past, Present & Future

Dick Bond Canadian Institute for Theoretical Astrophysics, University of Toronto

theory of CMB polarization

E/B modes

detection history

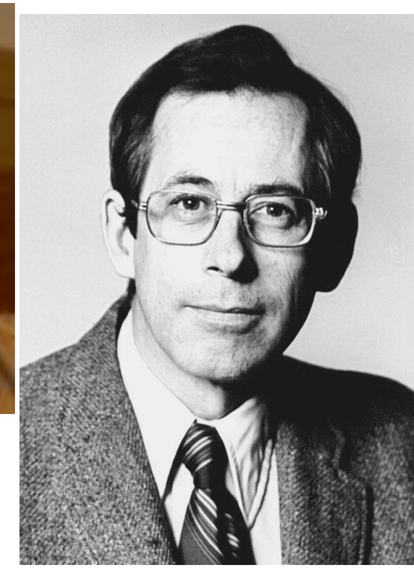
future CMB polarization experiments

reionization ‘trajectories’

inflation & forecasts of the gravity wave level: is the energy scale of inflation high (80s/90s) or low (00s)?

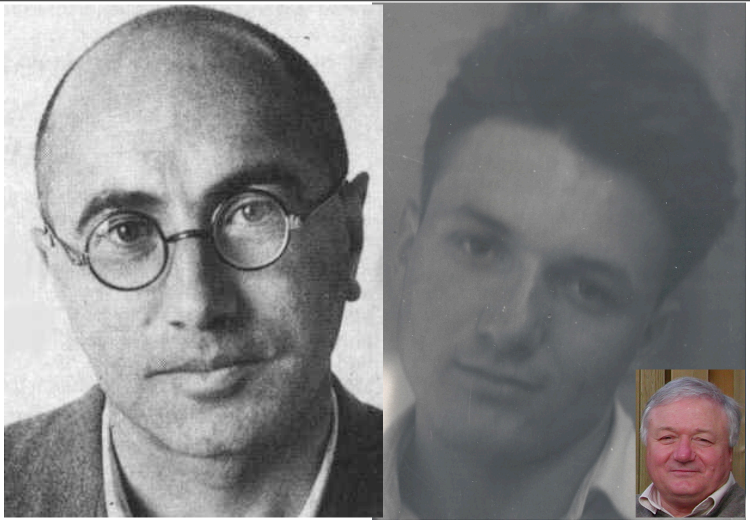
the quest for gravity wave induced B-modes



Peebles, Page, Partridge, *Finding the Big Bang*, *Feb09 CUP*

Rees 1968: CMB should be polarized; detection 2002 DASI



Peebles, Page, Partridge, *Finding the Big Bang,* ***Feb09 CUP***

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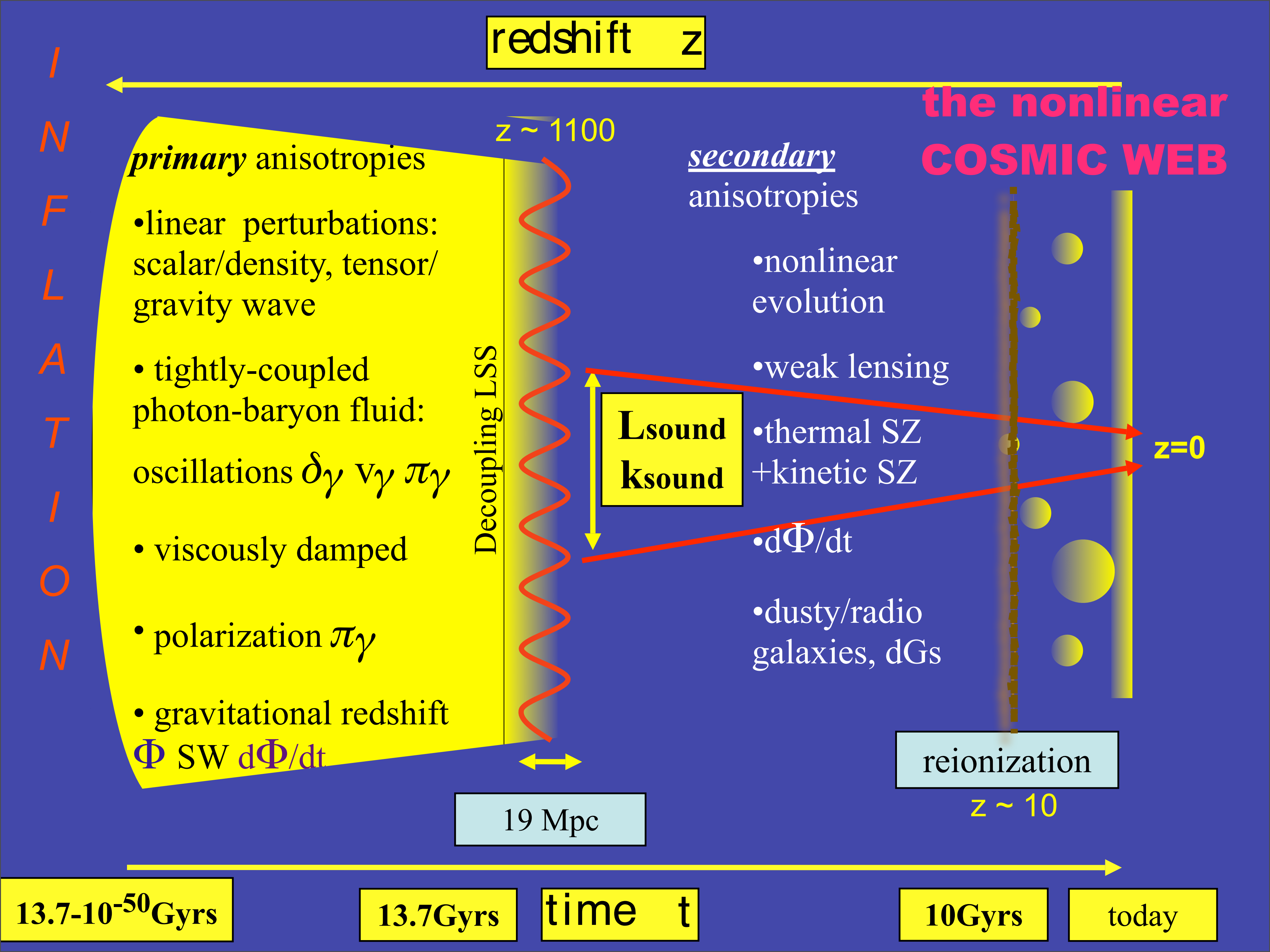


redshift z
INFLATION
z ~ 1100
the nonlinear
COSMIC WEB
primary anisotropies
•linear perturbations: scalar/density, tensor/ gravity wave
• tightly-coupled photon-baryon fluid:
oscillations $\delta\gamma$ $v\gamma$ $\pi\gamma$
• viscously damped
• polarization $\pi\gamma$
• gravitational redshift
Φ SW $d\Phi/dt$
Decoupling LSS
Lsound
ksound
secondary
anisotropies
•nonlinear evolution
•weak lensing
•thermal SZ
+kinetic SZ
•$d\Phi/dt$
•dusty/radio galaxies, dGs
z=0
reionization
z ~ 10
19 Mpc
$13.7\text{-}10^{-50}$Gyrs
13.7Gyrs
time t
10Gyrs
today

Peebles, Page, Partridge, *Finding the Big Bang,* **Feb09 CUP**

Rees 1968: CMB should be polarized; detection 2002 DASI

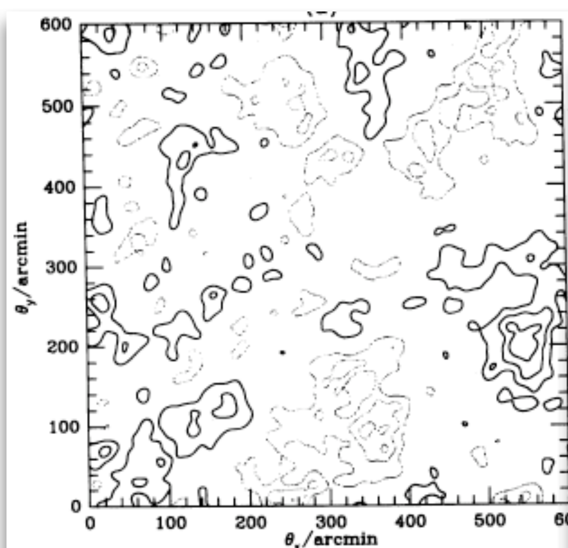
Kaiser83, pol via line-of-sight integration
BE84: pol via Boltzmann transport, ~7% target, effect on shear viscosity, damping tail, "E" mode
BE87: low to high L full CLpol, maps

First E detection DASI 2002; CBI04/05, Boom05, WMAP06, Capmap08, QuAD08; BICEP09?

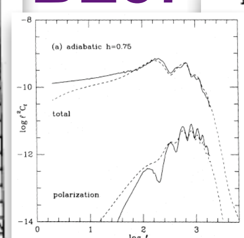
Delta T over Tea Toronto May 1987: first dedicated CMB conference, exptalists+theorists, primary+secondary ΔT/T

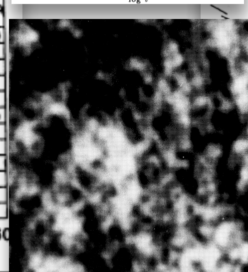
A tentative list of topics organized according to angular scale, with theory and observation intertwined, is:

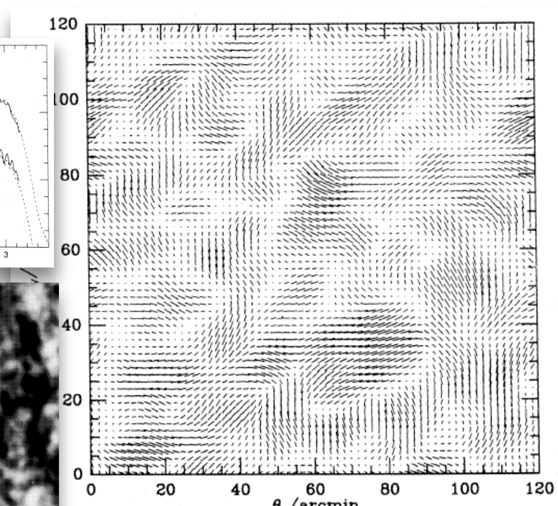
- very small angle anisotropies - VLA results, secondary fluctuations via the Sunyaev-Zeldovich effect, primeval dust emission, and radio sources
- small angle anisotropies - current results, optimal measuring strategies, statistical methods for small signals in larger noise, which universes can we rule out, the reheating issue, future detectors and techniques, CMB map statistics, polarization
- intermediate and large angle anisotropies - $5^o - 10^o$ results, future experiments at $\sim 1^o$, COBE and other large angle analyses, theoretical $C(\theta)'s$ and their angular power spectra, Sachs-Wolfe effect in open Universes, the isocurvature CDM and baryon stories, $\Delta T/T$ from gravitational waves, the cosmic string story.



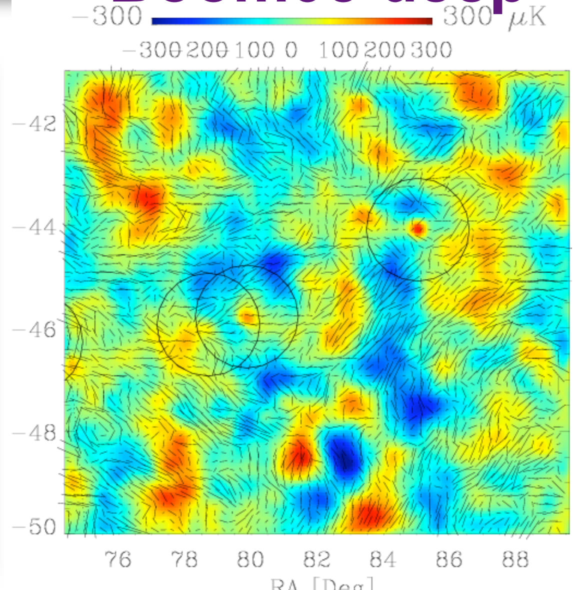
BE87







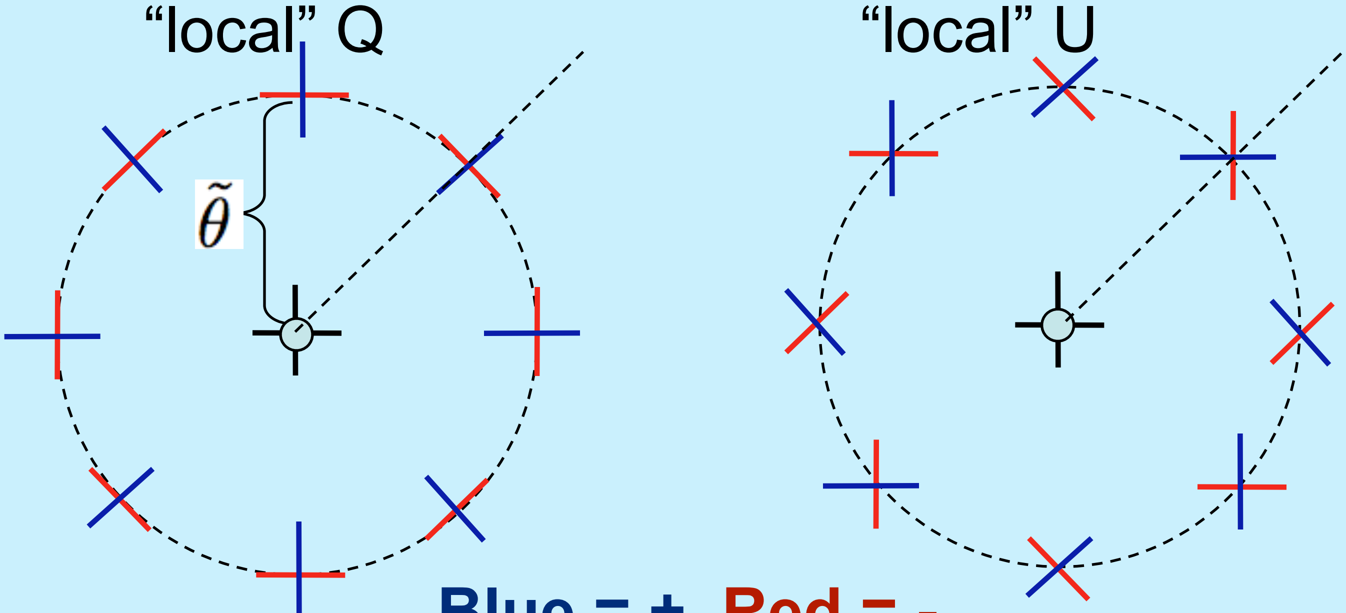
Boom05 deep



E and B modes: f(ss',xpt) Stokes parameters I,Q,U,V with Q-only for Thompson scattering in a plane parallel atmosphere Chandrasekhar...BE84...

scalar polarization basis in Fourier space E=Q(**q**), B=U(**q**), q=L+1/2

large sky patches: $Q + iU(\hat{\mathbf{n}}) = \sum_{lm} {}_2a_{lm}\ {}_2Y_{lm}$ $Q - iU(\hat{\mathbf{n}}) = \sum_{lm} {}_{-2}a_{lm}\ {}_{-2}Y_{lm}$



Tensor perturbations, transverse-traceless metric h_+, h_x **& neutrino+photon anisotropic stress:** U & Q in **q**-space, i.e., **B & E**

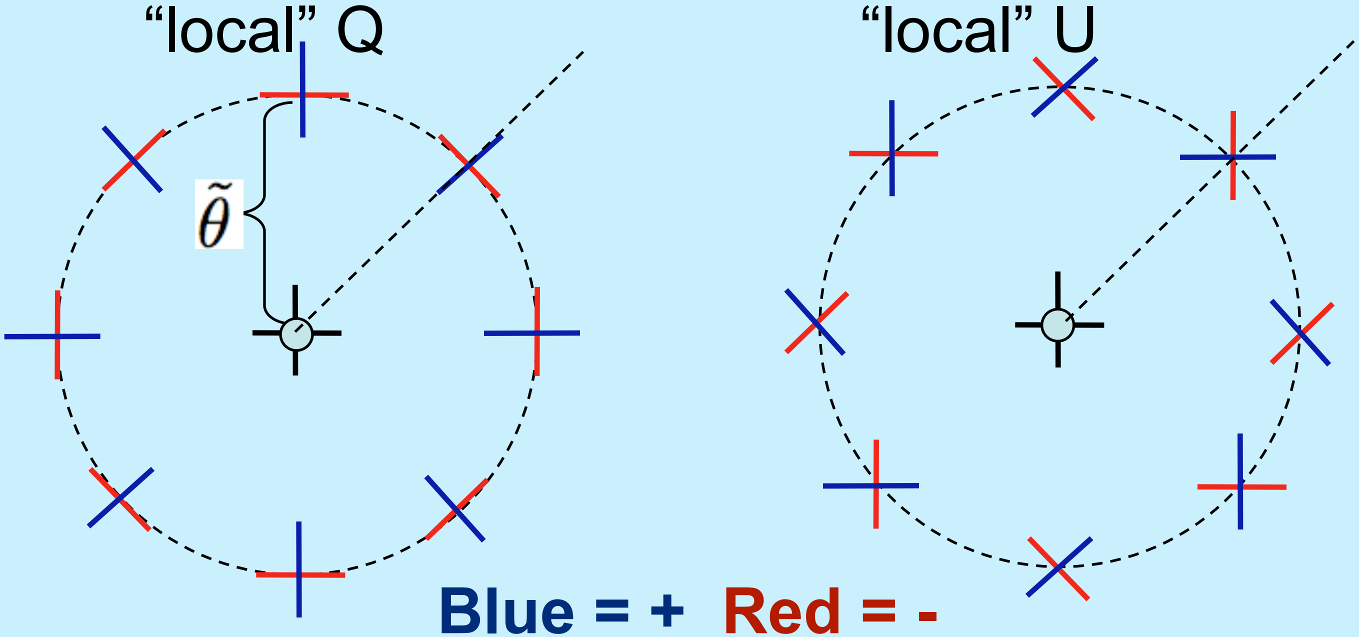
"fgnd" lensing by the cosmic web shifts scalar E pattern inducing B & E

"fgnd" Galactic & extragalactic sources give **B &E** separate by frequency, spatial pattern

E and B modes: f(ss',xpt) Stokes parameters I,Q,U,V with Q-only for Thompson scattering in a plane parallel atmosphere Chandrasekhar...BE84...

scalar polarization basis in Fourier space E=Q(**q**), B=U(**q**), q=L+1/2

large sky patches: $Q+iU(\hat{\mathbf{n}}) = \sum_{lm} {}_2a_{lm}\ {}_2Y_{lm}$ $\quad Q-iU(\hat{\mathbf{n}}) = \sum_{lm} {}_{-2}a_{lm}\ {}_{-2}Y_{lm}$



$$a^E_{lm} = -(\ {}_2a_{lm} + \ {}_{-2}a_{lm})/2 \quad a^B_{lm} = i(\ {}_2a_{lm} - \ {}_{-2}a_{lm})/2$$

Tensor perturbations, transverse-traceless metric h_+, h_x **& neutrino+photon anisotropic stress:** U & Q in **q**-space, i.e., **B & E**

"fgnd" lensing by the cosmic web shifts scalar E pattern inducing B & E

"fgnd" Galactic & extragalactic sources give **B &E** separate by frequency, spatial pattern

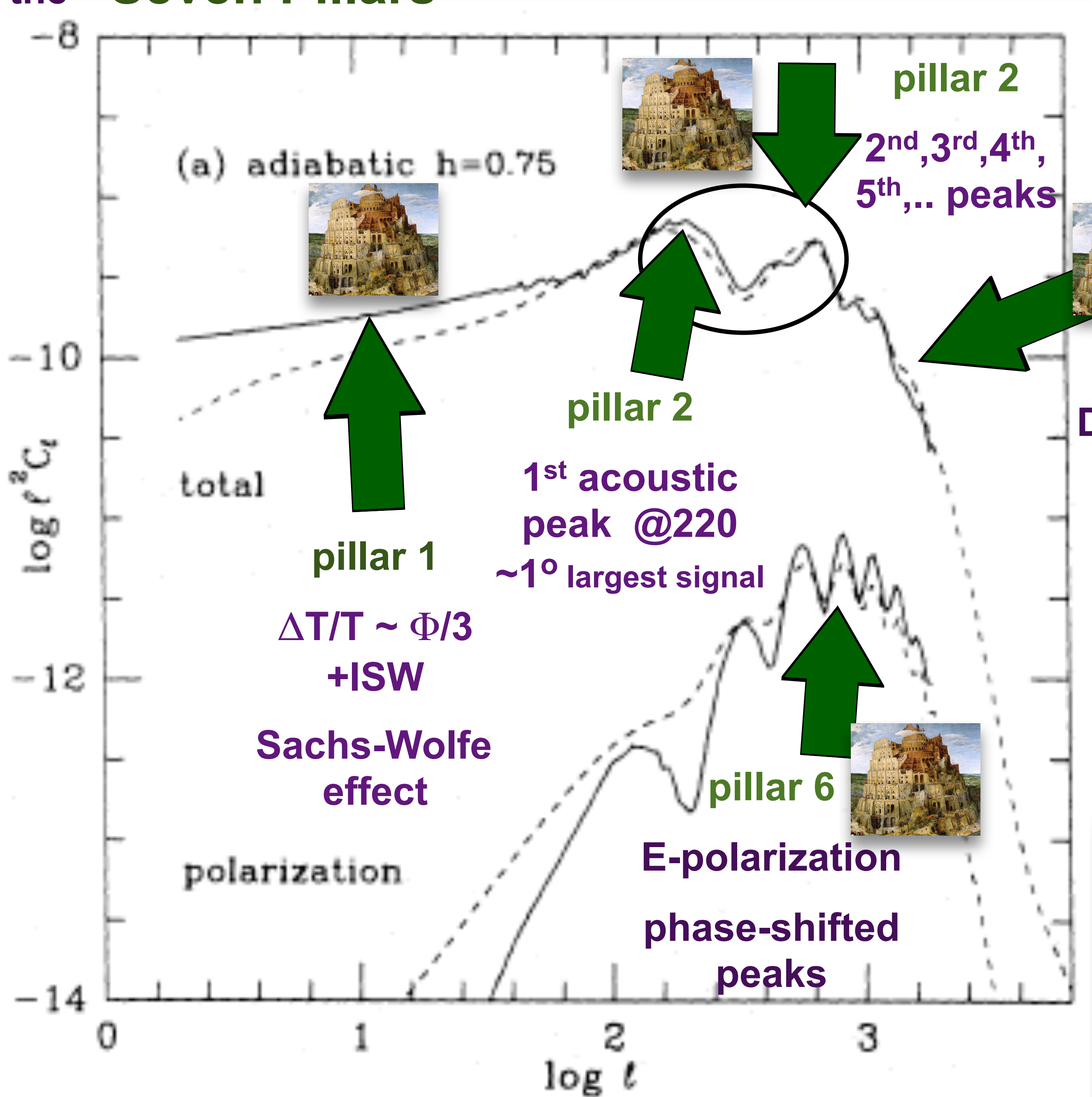
Peebles, Page, Partridge, *Finding the Big Bang*, Feb09 CUP

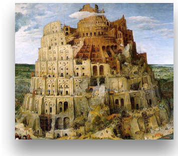
Rees 1968: CMB should be polarized; detection 2002 DASI

Kaiser83, pol via line-of-sight integration
BE84: pol via Boltzmann transport, ~7% target, effect on shear viscosity, damping tail, "E" mode
BE87: low to high L full CLpol, maps
Crittenden & Turok 96: TE correlation **DASI02,WMAP03**
Kaiser95, Stebbins96: rotate lensing E to B, a null test
Kamionkowski, Kosowsky & Stebbins97 & Seljak & Zaldarriaga97: apply to CMB E/B modes. emphasize as gravity wave discriminator
Zaldarriaga & Seljak98 lensing distorts E into B

First E detection DASI 2002; CBI04/05, Boom05, WMAP06, Capmap08, QuAD08; BICEP09?

the “Seven Pillars”



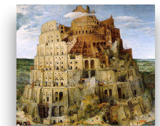


pillar 4

Gaussianity
maximal randomness
for given C_L

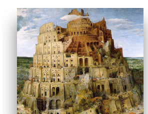
pillar 3

Damping tail



pillar 5

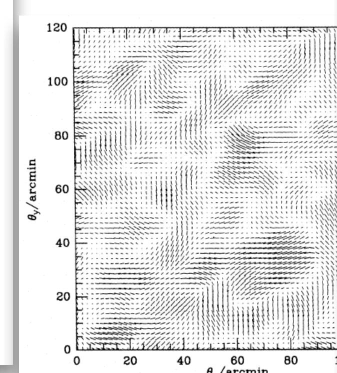
secondary ΔT
nonlinear
Compton SZ
weak lensing..



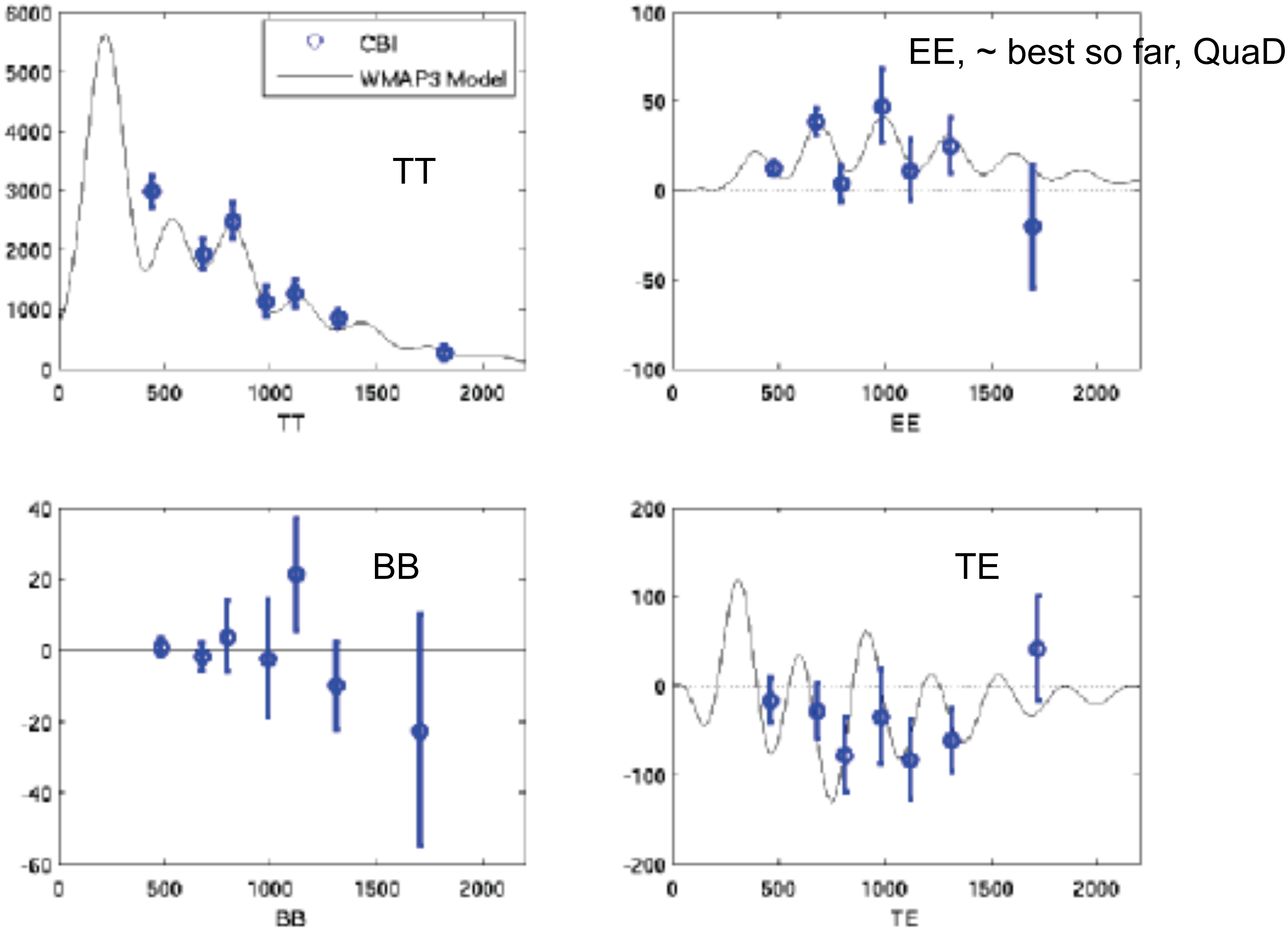
pillar 7

B-polarization

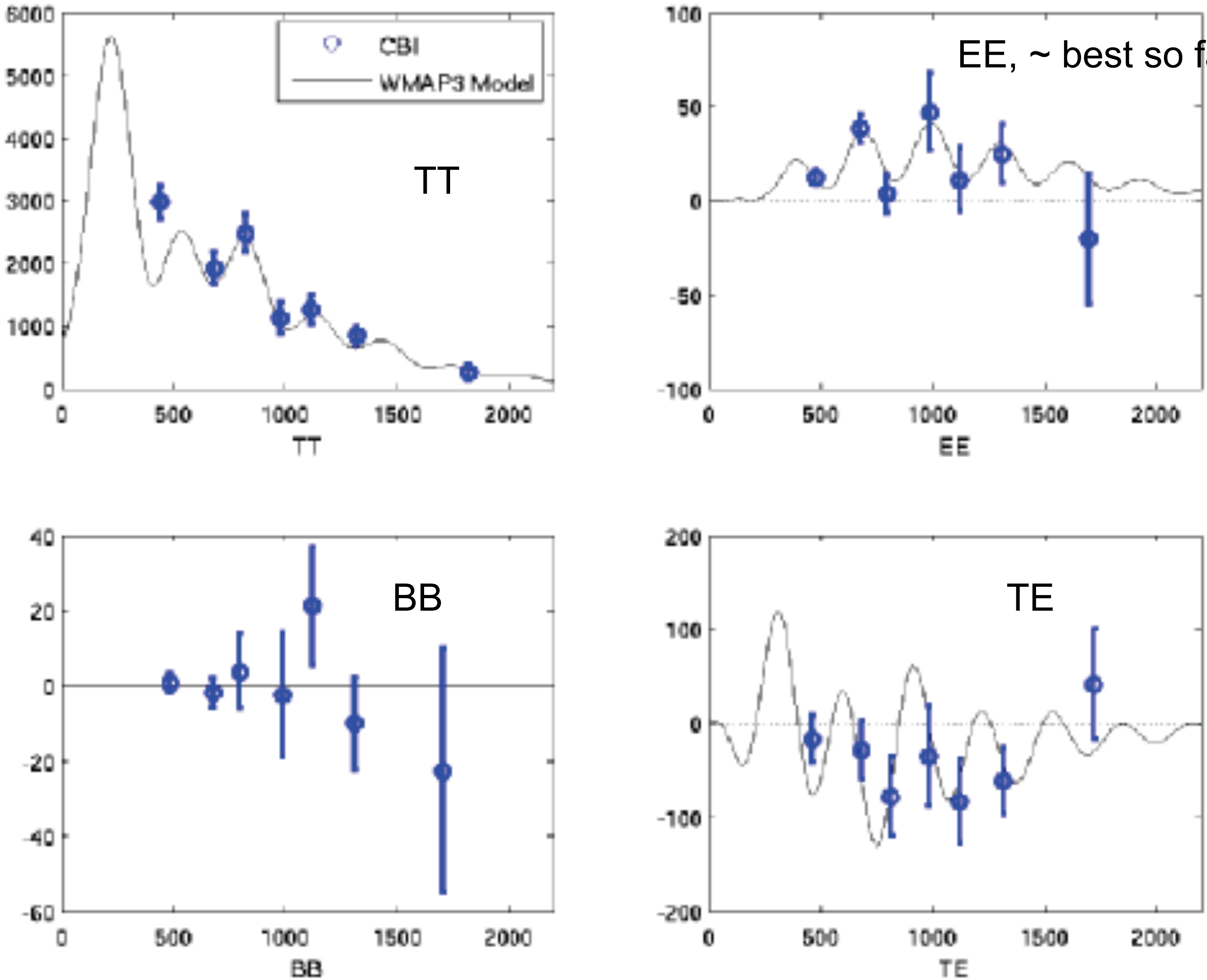
Gravity Waves



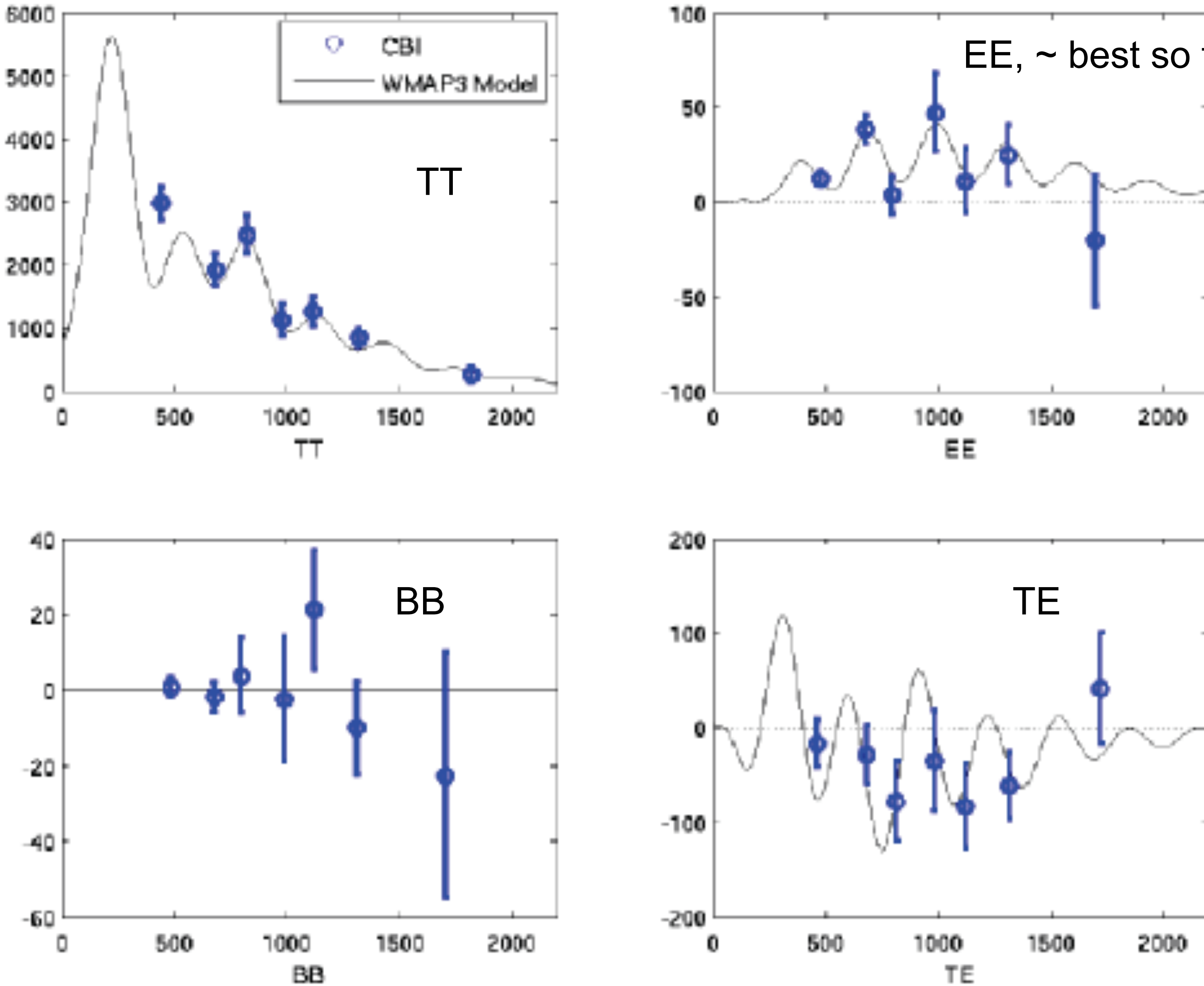
CBIpol 2.5yrs Sievers etal 05/06, Readhead etal 04



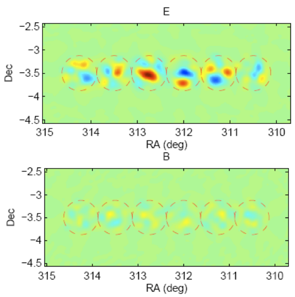
CBIpol 2.5yrs Sievers etal 05/06, Readhead etal 04



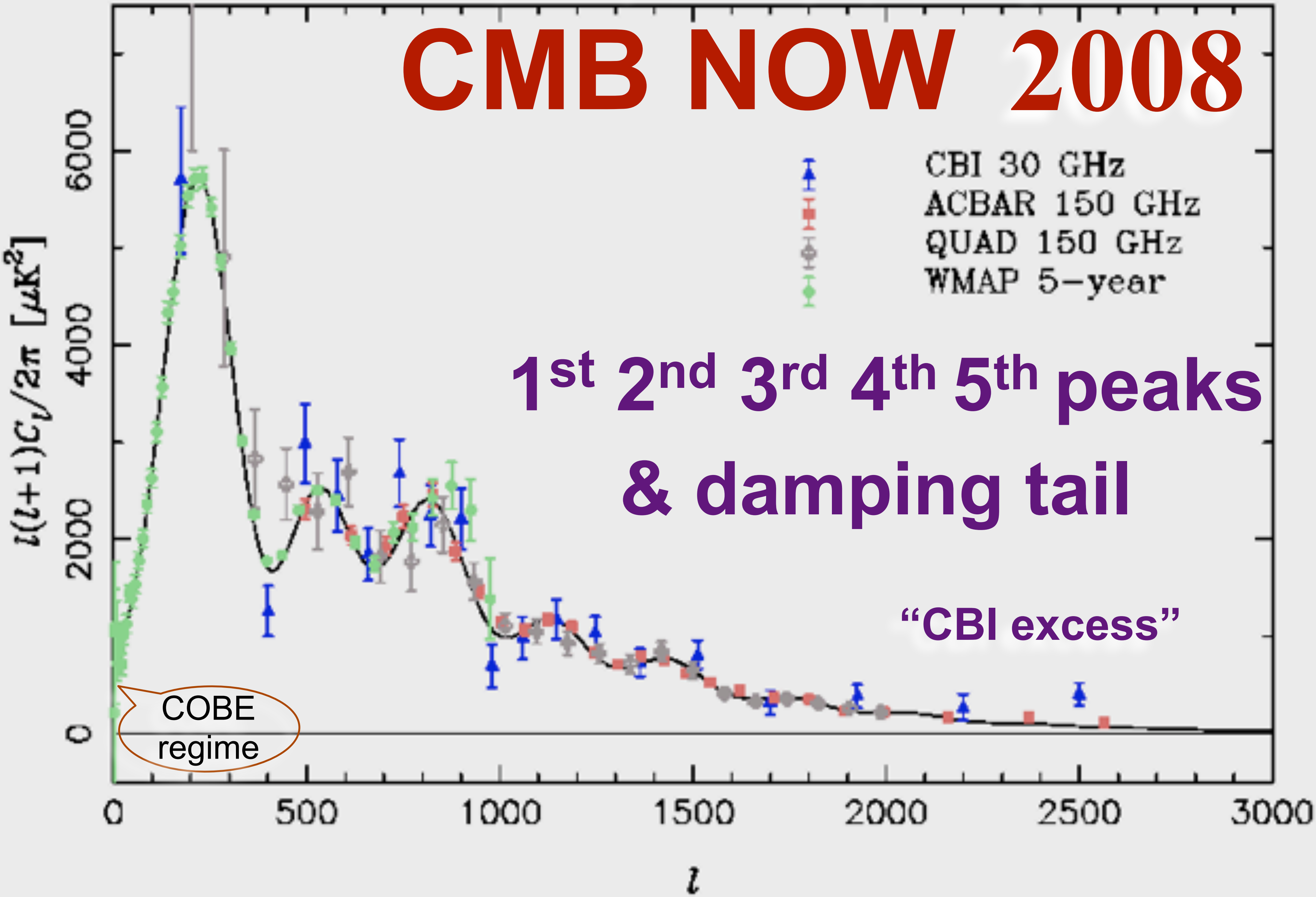
CBIpol 2.5yrs Sievers etal 05/06, Readhead etal 04



EE, ~ best so far, QuaD

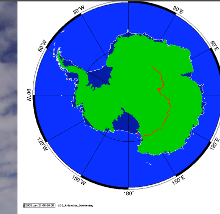


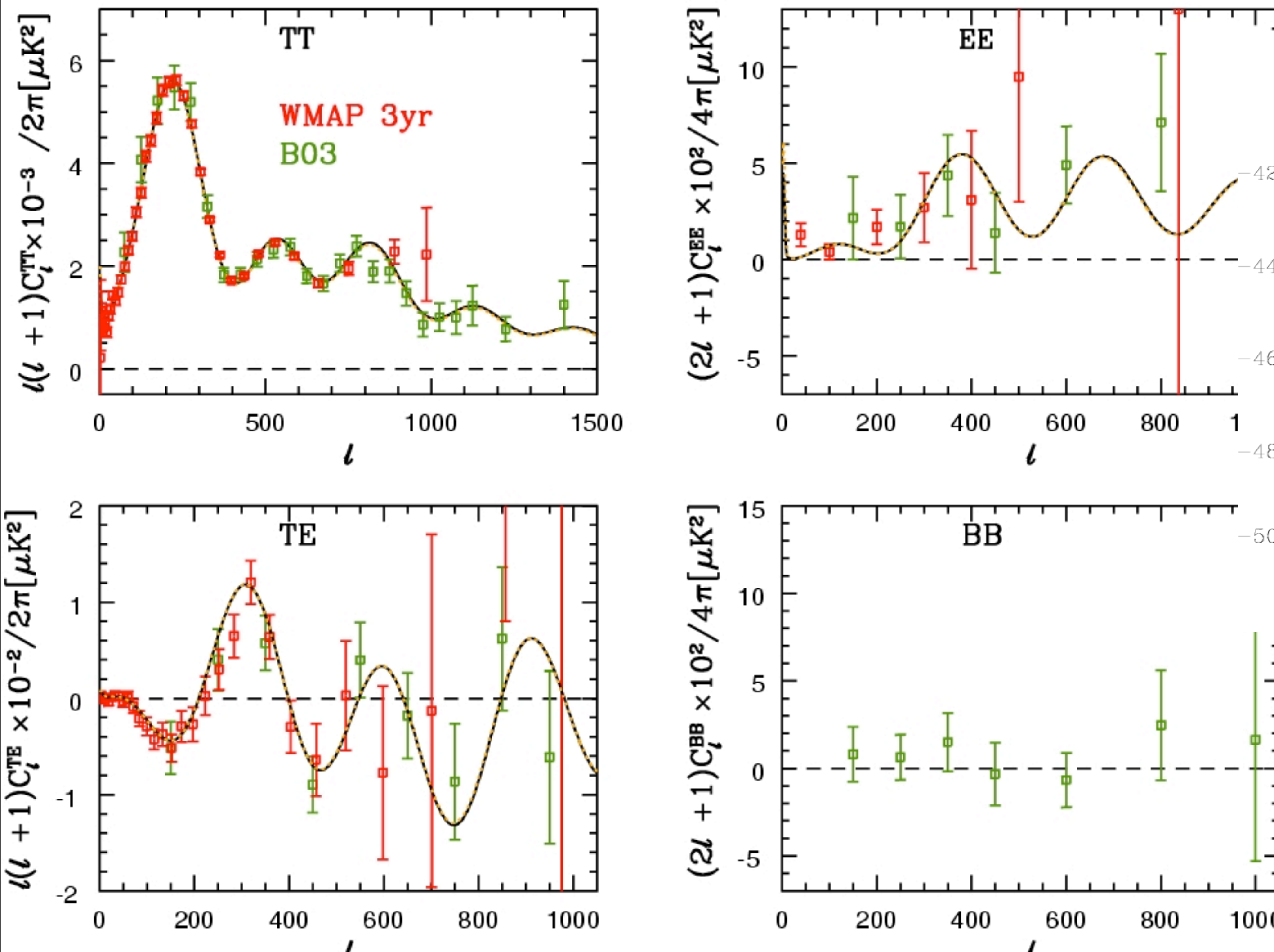
Sievers etal 2008 Dec astroph CBI5yrs, still 2.5yrs pol, so slight effect on TE

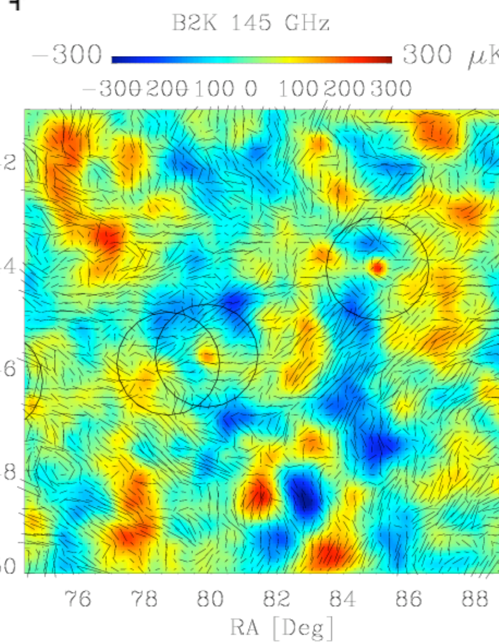


B03 pol TE, EE 2005 1st bolo detection

- ‘Shallow’ scan, 75 hours, f_{sky}=3.0%, large scale TT
- ‘deep’ scan, 125 hours, fsky=0.28% 115sq deg, ~ 2 X Planck2yr







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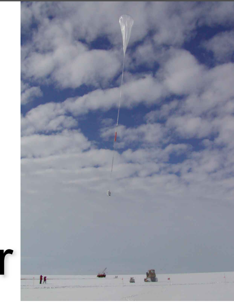
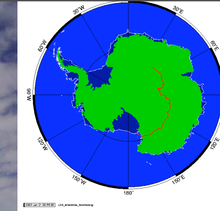
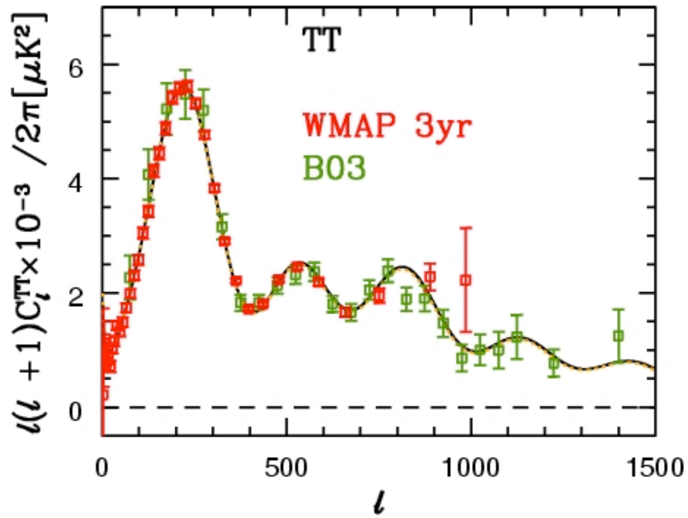
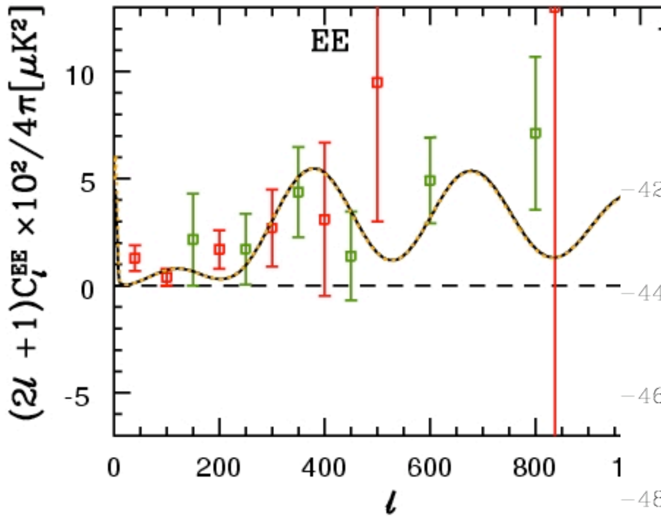
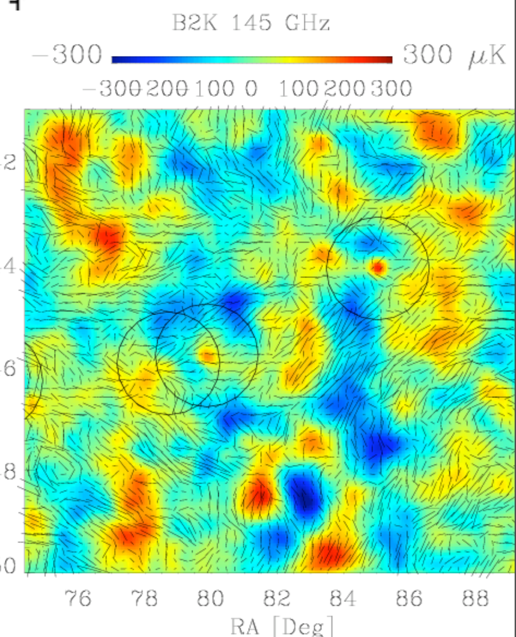
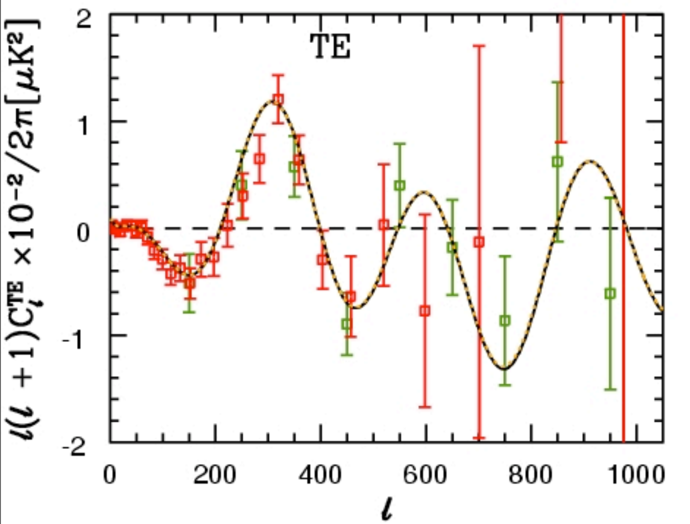


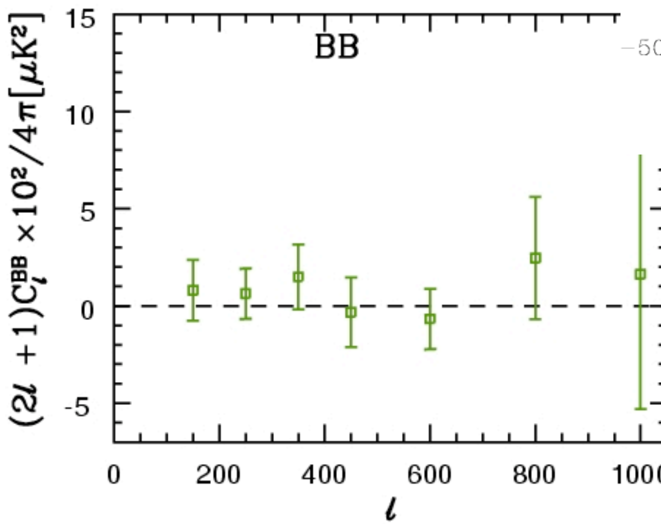


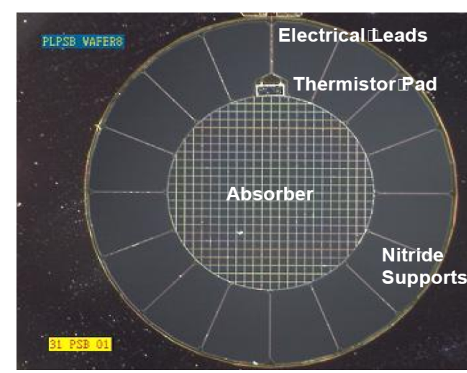






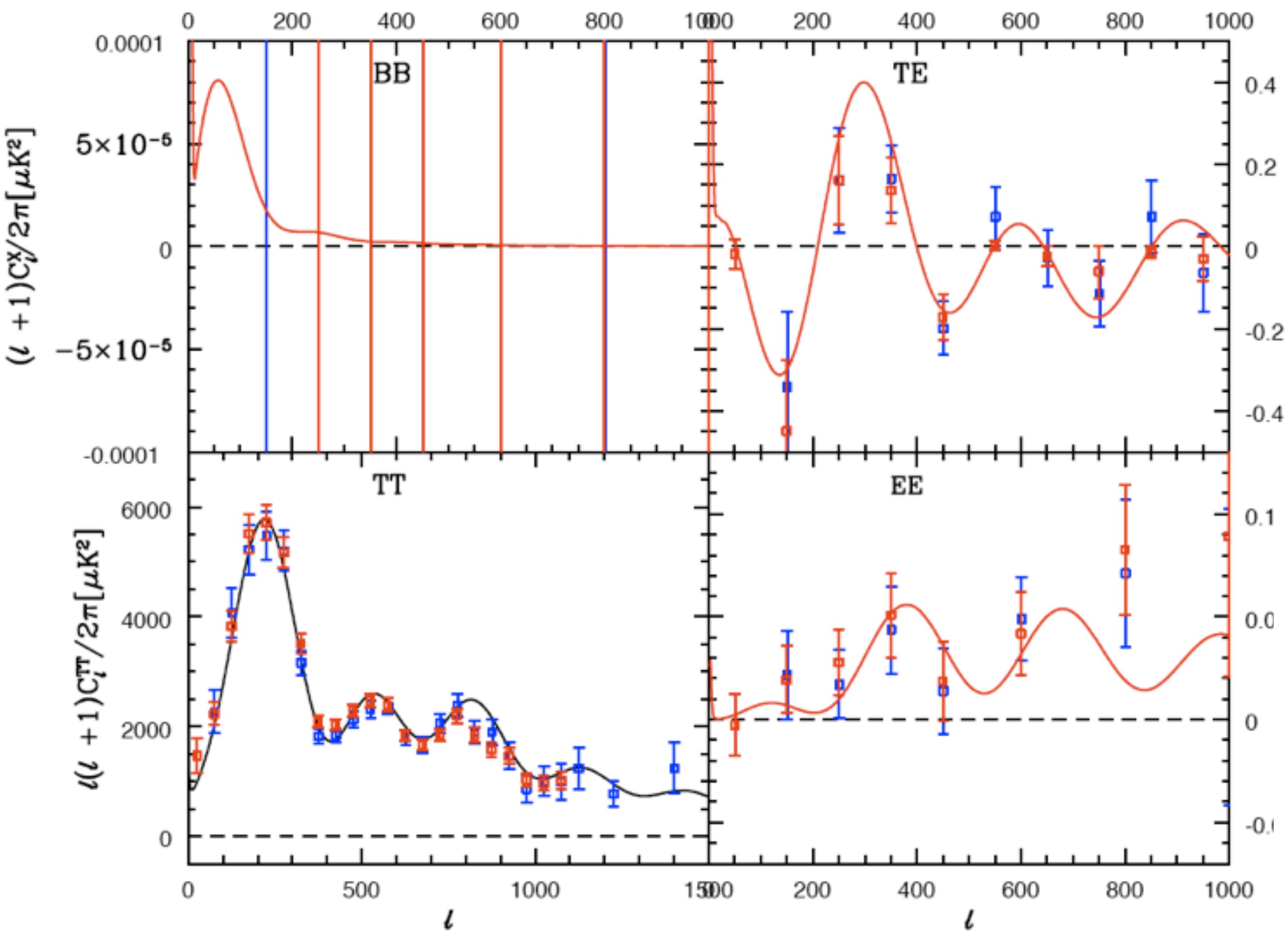


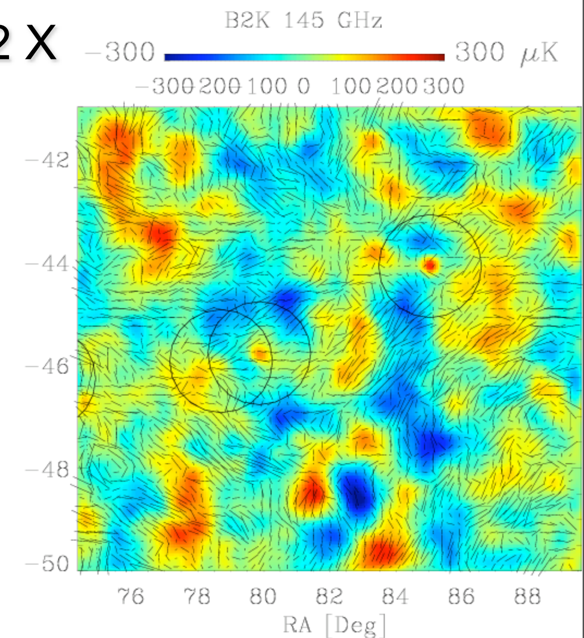


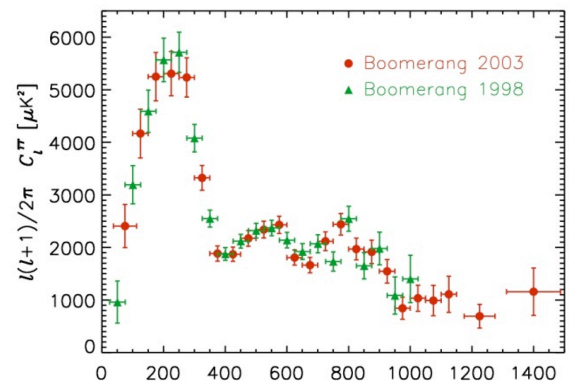


B03+B98 *Contaldi etal 01..09!* **xfaster!** *Boom/Planck/Spider workhorse*

- 'Shallow' scan, 75 hours, f_{sky}=3.0%, large scale TT
- 'deep' scan, 125 hours, fsky=0.28% 115sq deg, ~ 2 X Planck2yr



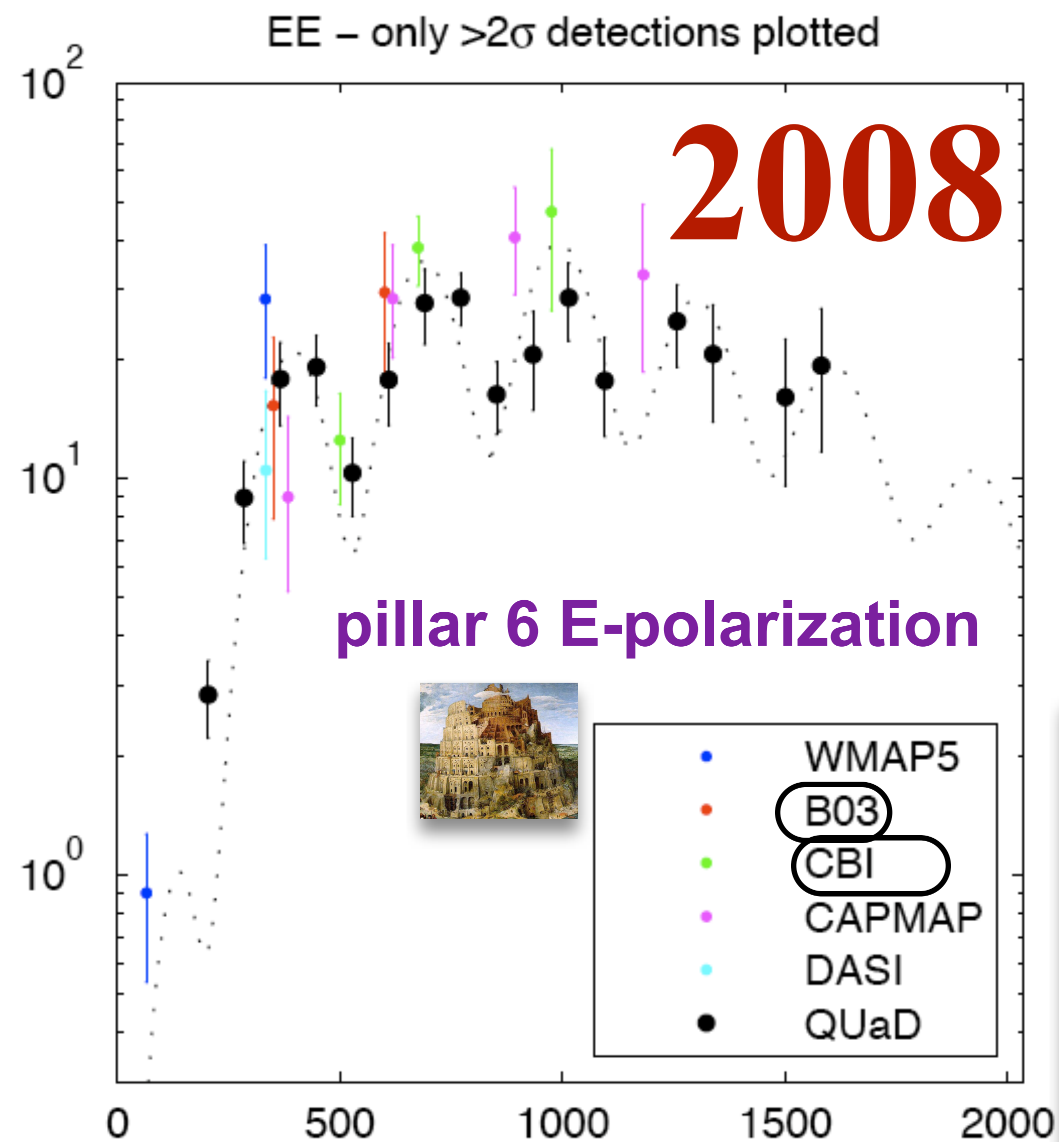


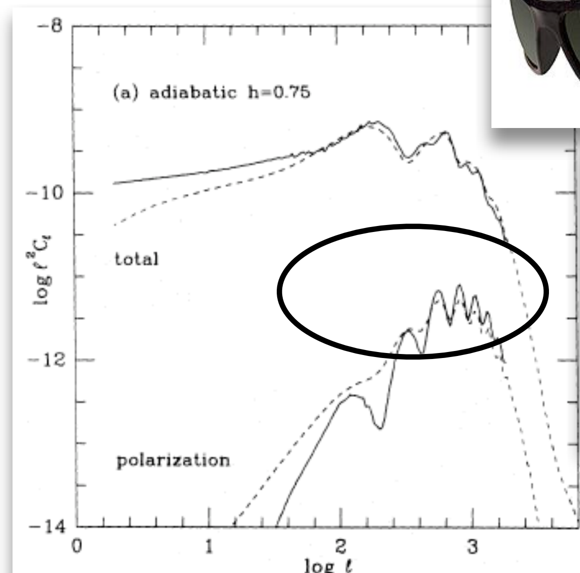


B03+B98 final soon

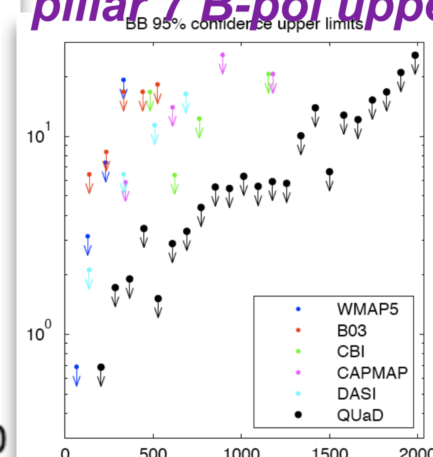
emergence of CMB polarization *power*

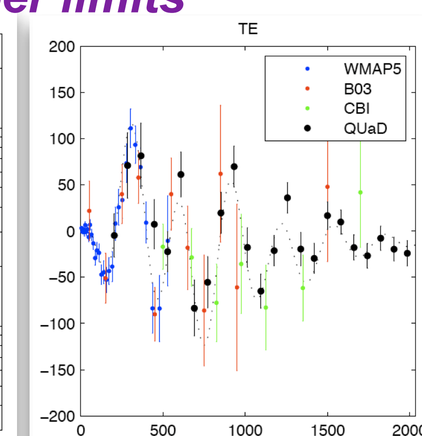
DASI02,04 CBI04 Boom05 CBI05 WMAP3,5 Capmap07 QUaD07,08





pillar 7 B-pol upper limits





What do we learn from E polarization?

0 - EE/TE agree with TT forecasts! *pillar6: out-of-phase pks/valleys*

1 - constrain radically broken scale invariance *out-of-phase pks*

2 - constrain subdominant isocurvature modes CBI

3 - constrain anomalies *e.g., WMAP haze, COBE/WMAP "hole" TBD*

4 - aid in lensing reconstruction of lensed CMB *TBD*

5 - aid in separation of components, dust & synchrotron; *SZ*

WMAP1 .166+-.08 TE, WMAP3 .089+-.03 EE fgnd-clean,
WMAP5 .086+-.016, WMAP5 .090+-.019 GibbsMCMC; Planck1yr 09.3+1.5yr +-.005;
Spider test flight 2-6d, 2010.3, Alice Springs, +-.007

6- reionization epoch

τ_C = l.o.s.-int $n_e \sigma_T$ cdt

$\sim$**.1** $((1+z_{reh})/15)^{3/2}$

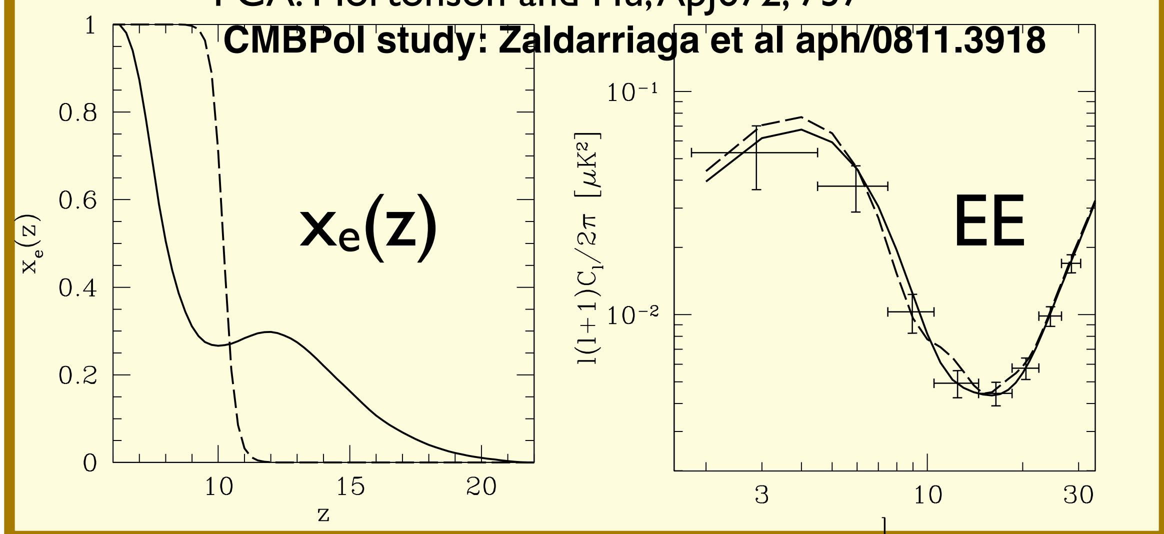
$(\Omega_b h^2/.02)(\Omega_m h^2/.15)^{-1/2}$

0.085+- .017 CMBall$_{cbi10}$

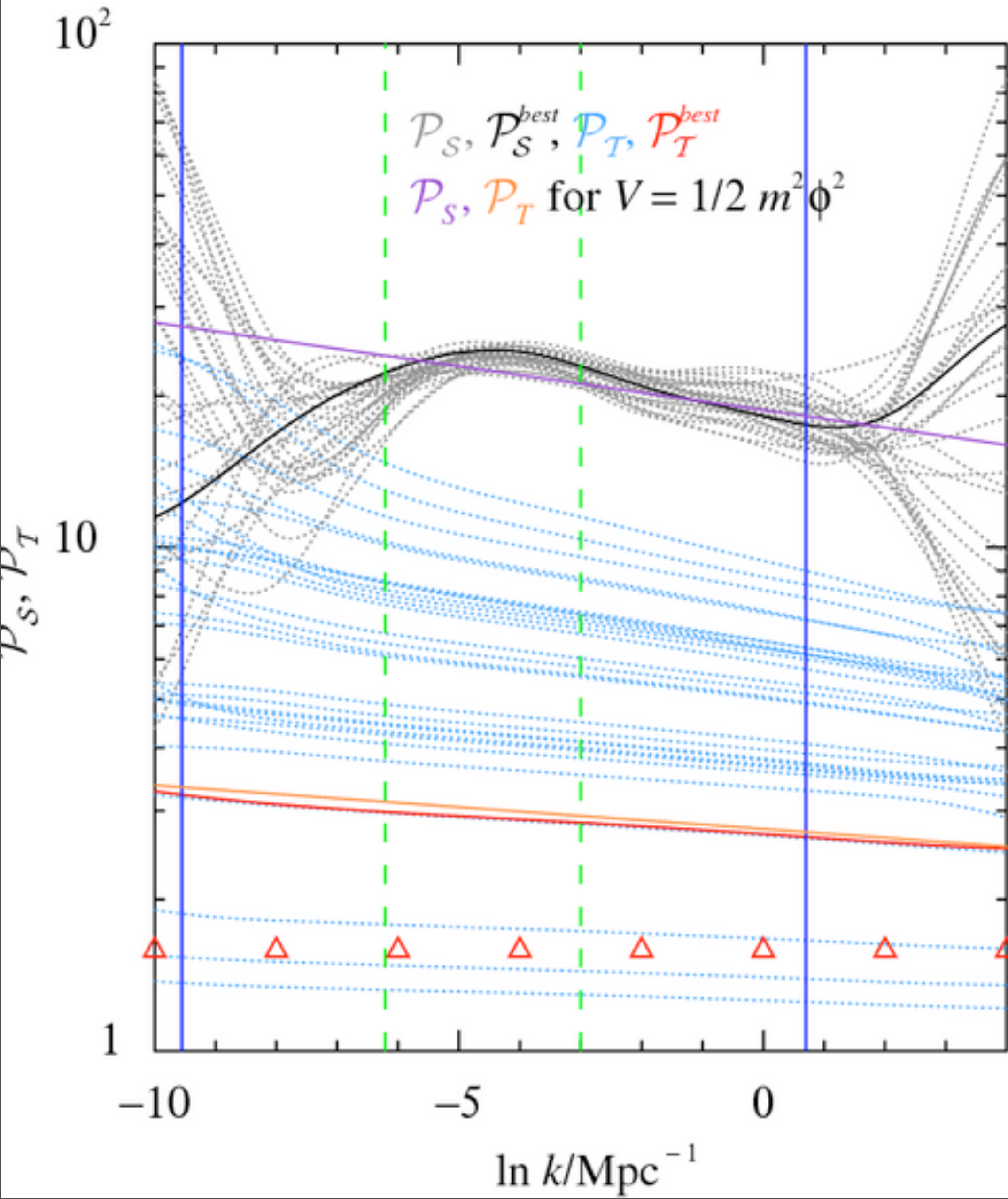
z_{reh} **=0.8 +- 1.5**

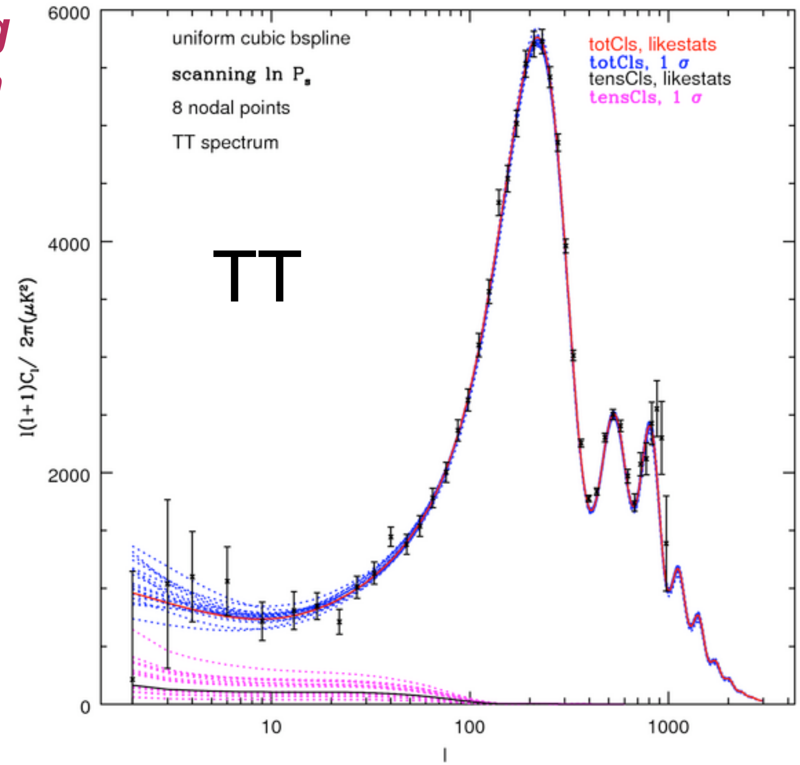
PCA: Mortonson and Hu, ApJ672, 737

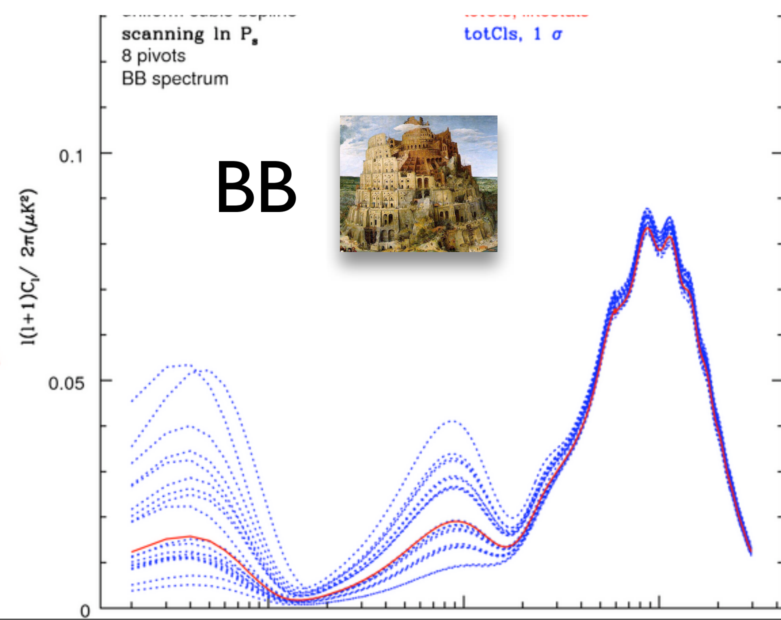
CMBPol study: Zaldarriaga et al aph/0811.3918



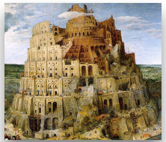
partially-blind acceleration trajecteries obeying tensor/scalar consistency relation. May08 data



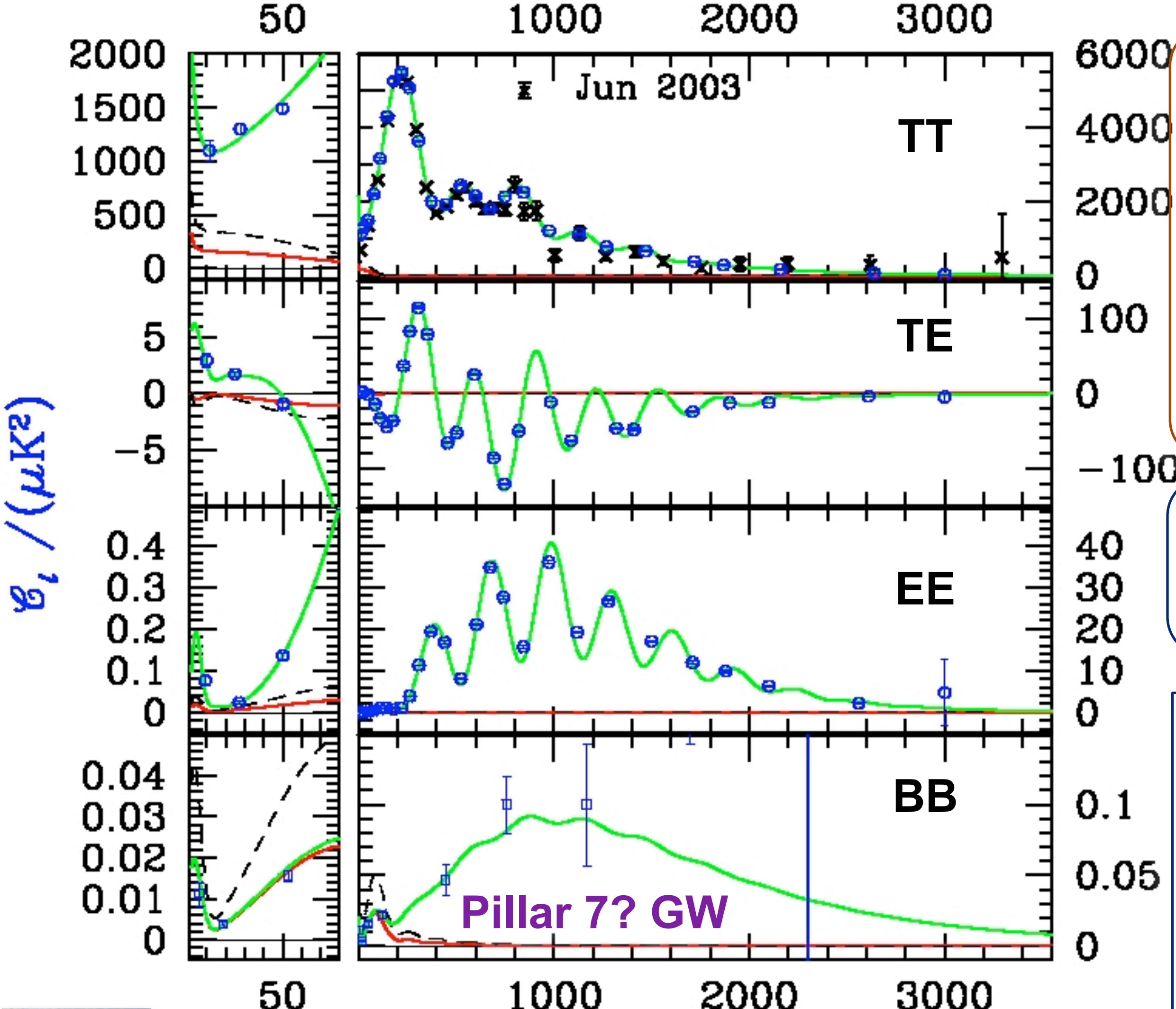




PRIMARY END @ 2012?



CMB ~2009+ Planck1+WMAP8+SPT/ACT/Quiet+Bicep/QuAD/Quiet +Spider+Clover



Pillar 7? Gravity Waves

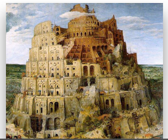
An ensemble of trajectories arises in many-moduli string models, whether braney or holey. **Roulette inflation:** ***complex hole sizes in 6D*** TINY **$r<10^{-10}$** ***& n_s from data-selected braking!***

('theorem': $\Delta\psi$< 1 -> **r<.007**)

nearly uniform acceleration (power law, exp, PNGB, ..potentials)

r~.03-.3! is $\Delta\psi$~10 deadly?

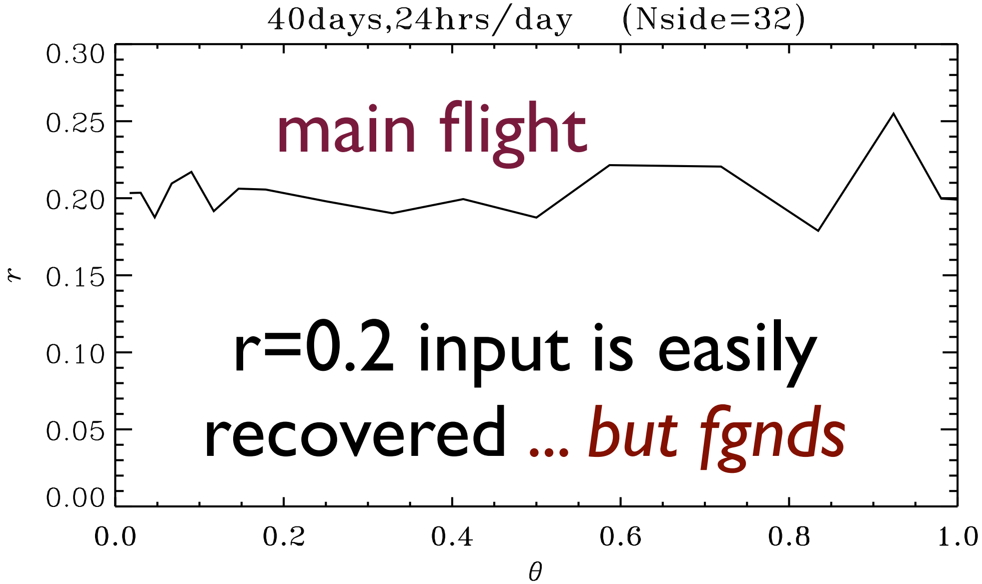
Even with low energy inflation, the prospects are good with Spider plus Planck to either detect the GW-induced B-polarization or set a strong blind upper limit r<0.02 indicating stringy or other exotic models. Both experiments have strong Cdn roles. Bpol 2020?, to r~0.002



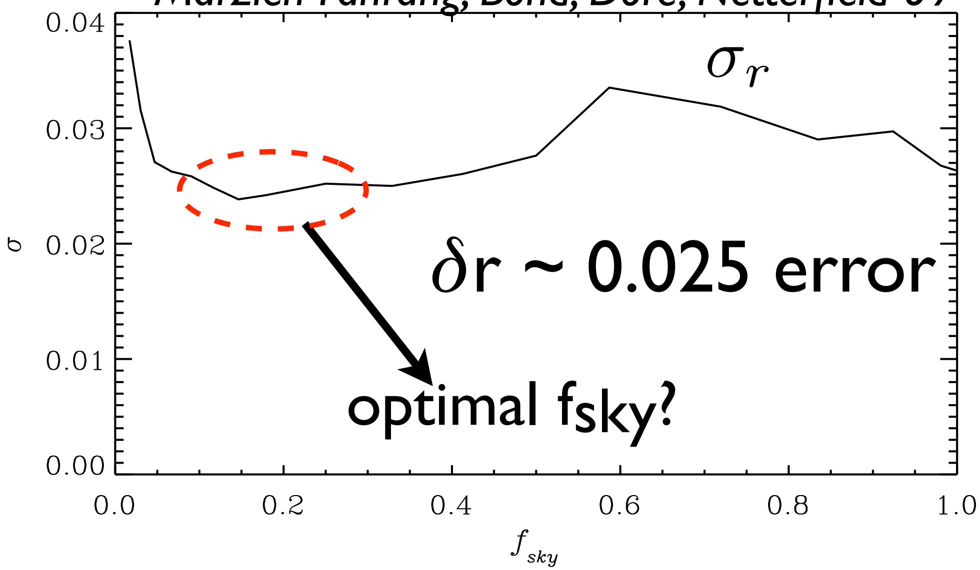
+ Pillar 4: primordial non-Gaussianity **$-9< f_{NL} <111$ (+- 5-10 Planck1)**

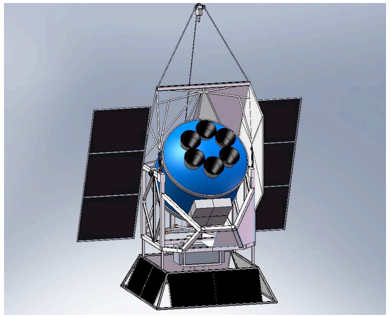
Spider/Keck: best f_{sky} for E/B-demixing via direct max-L filters for **r** τ

- test LDB flight: 2-6 days, 10.3 Alice Springs
- **main LDB flight: 20-40 days, 11.9 Antarctica**
  N_t~2.5 Tbytes, N_p~10 Mb



Marzieh Fahrang, Bond, Dore, Netterfield 09





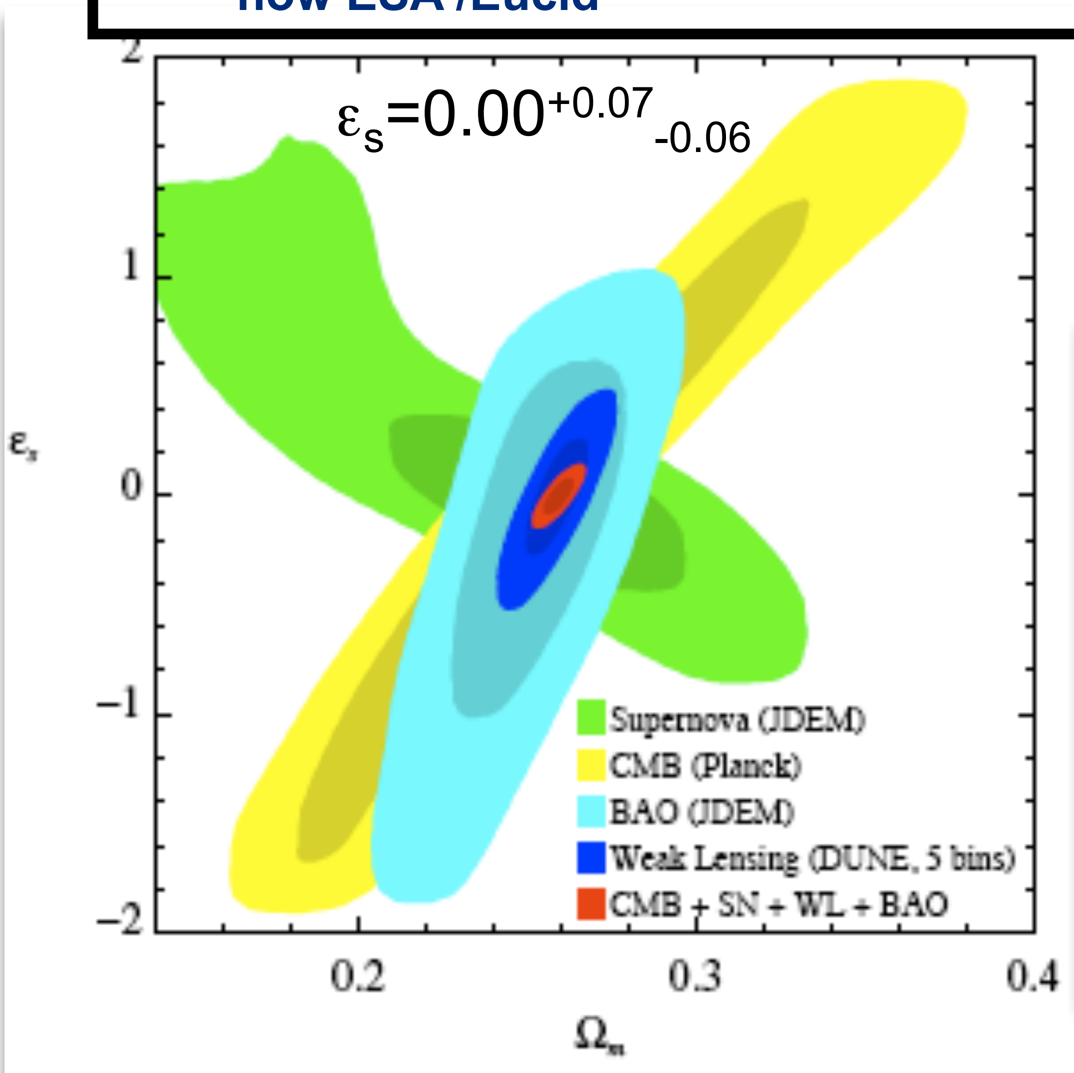
Beyond Einstein panel: LISA+JDEM

Forecast: **JDEM-SN** (2500 hi-z + 500 low-z)

+ **DUNE-WL** (50% sky, gals @z = 0.1-1.1, 35/min^2) + **Planck1yr**

now ESA /Eucid

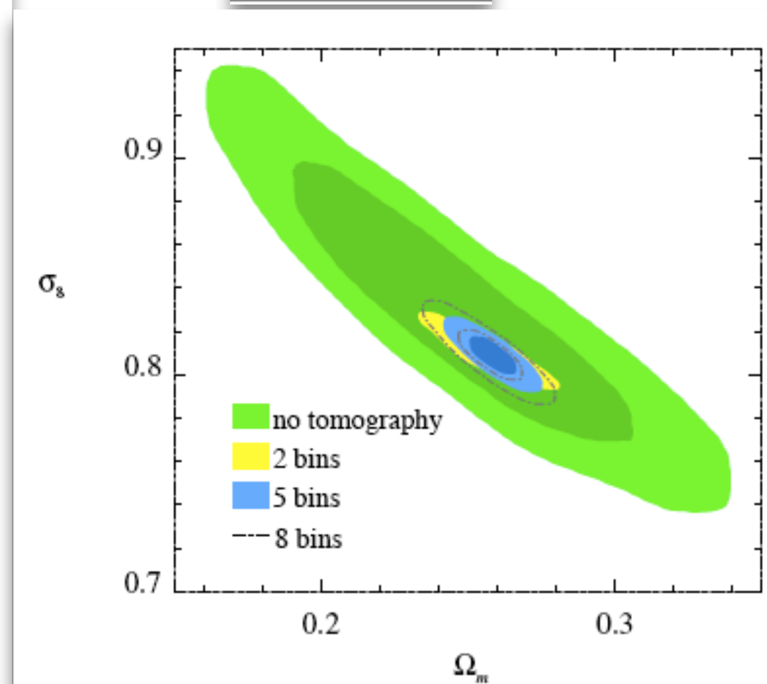
ESA (+NASA/CSA)



a_s=0 case

ζ_s ~dlnε_s /dlna /2 ill-determined

$0.1^{+0.6}_{-0.7}$



cannot reconstruct the quintessence potential, just the slope ε_s & ~hubble drag

Standard Parameters of Cosmic Structure Formation

$\Omega_b h^2$ $\Omega_{dm} h^2$ Ω_Λ Ω_k τ_c $\ln A_s$ n_s $r = A_t/A_s$ $dn_s/d\ln k$ n_t

$1+w_0$, w_a $\theta \sim \ell_s^{-1}$ $n_e(a)$ $\sim \ln \sigma_8^2$

New Parameters of Cosmic Structure Formation: early-inflaton & late-inflaton trajectories (& reionization histories)

$\varepsilon_\phi = (1+w(a)) \times 3/2 = -d\ln\rho_\phi/d\ln a/2$

$\varepsilon_s f(a/a_{\Lambda eq}; a_s/a_{\Lambda eq}; \zeta_s)$

$\ln P_s(\ln k)$ & $r(k_p)$ & $\ln P_t(\ln k)$

Blind trajectory analysis cf. data, then & now

expand $\varepsilon(\ln k)/\varepsilon_\phi(\ln a)$ in localized mode fns

e.g., **Chebyshev/B-spline coefficients ε_b**

ε_b-measures: "theory prior"=*informed prior?*

$\varepsilon_\phi(\ln k)$, $k \sim Ha$ & $\ln H(k_p)$

+ subdominant

isocurvature/ cosmic string/ tSZ ...